UNIVERSIDADE DE LISBOA

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As-built building information modeling (BIM) workflows: from point cloud data to BIM

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2D Two dimensional

3D Three dimensional

4D BIM + Schedule (Time) = 4D

5D BIM + Cost = 5D

A

AEC Architecture, Engineering and Construction

AI Artificial Intelligence

AIM Architectural Information Modelling

AM Architectural Memory

API Application Programming Interface

ADP Automatic Digital Photogrammetry

B

BIM Building Information Modelling

BIMs Building Information Model

C

CA(A)D Computer-Aided (Architectural) Design

CAMS Computer-Aided manual Surveying

CEN European Committee for Standardization

CFD Computational Fluid Dynamics

COBie Construction Operation Building Information Exchange

CWM Closed World Machine

D

DCC Dynamic Content Creation DL Description Logic

DWG Drawing (is a binary file format used for storing two and three dimensional design data and metadata. It is the native format for several CAD packages.)

E

EYE Euler Yap Engine

F

FBM Feature-Based Modelling

FM Facility Management

G

GUI Graphical User Interface

H

HTML HyperText Markup Language

HTTP HyperText Transfer Protocol

I

ICT Information and Communication Technology

IFC Industry Foundation Classes

L

LOD Level of Development

LID Level of Information Detail

LOC Level of Certainty

M

MACE Metadata for Architectural Contents in Europe

MR Mixed Reality

MVS Multi-view-stereo

N

NBN National Bureau for Normalization

O

OLE Object Linking and Embedding

OWL Web Ontology Language

P

PLM Product Lifecycle Management

PCM Point Cloud Model

Q

QA Quality Assurance

QC Quality Control

R

RDF Resource Description Framework

RDFS Resource Description Framework Schema

RIF Rule Interchange Format

RTS Robotic Total Station

S

SDK Software Development Kit

SFM Structure From Motion

SPARQL Simple Protocol and RDF Query Language

SQL Standard Query Language SWRL Semantic Web Rule Language

T

TLS Terrestrial Laser Scanning

U

UG-EPW UGent - Energie Prestatie in Woningen (Energy Performance in Residential Buildings)

URI Unique Resource Identifier

V

VRVS Virtual Reality - Visual Simulation

VSC Virtual Simulation and Calculation

W

W3C World Wide Web Consortium

WWW World Wide Web

X

X3D eXtensible 3D

XML eXtensible Markup Language

Y

YAP Yet Another Prolog

English summary

Building information modeling (BIM) is most often used for the construction of new buildings. By using BIM in such projects, collaboration among stakeholders in an architecture, engineering and construction project is improved. This scenario might also be targeted for interventions in existing buildings. This thesis intends to enhance processes of recording, documenting and managing information by establishing a set of workflow guidelines to efficiently model existing structures with BIM tools from point cloud data, complemented with any other appropriate methods.

There are several challenges hampering BIM software adoption for planning interventions in existing buildings. Volk et al. (2014) outlines that the as-built BIM adoption main obstacles are: the required modeling/conversion effort from captured building data into semantic BIM objects; the difficulty in maintaining information in a BIM; and the difficulties in handling uncertain data, objects, and relations occurring in existing buildings. From this analysis, it was developped a case for devising BIM workflow guidelines for modeling existing buildings. The proposed content for BIM guidelines includes tolerances and standards for modeling existing building elements. This allows stakeholders to have a common understanding and agreement of what is supposed to be modeled and exchanged.In this thesis, the authors investigate a set of research questions that were formed and posed, framing obstacles and directing the research focus in four parts: 1. the different kind of building data acquired; 2. the different kind of building data analysis processes; 3. the use of standards and as-built BIM and; 4. as-built BIM workflows and guidelines for architectural offices.

From this research, the authors can conclude that there is a need for better use of documentation in which architectural intervention project decisions are made. Different kind of data, not just geometric, is needed as a basis for the analysis of the current building state. Non-geometric information can refer to physical characteristics of the built fabric, such as materials, appearance and condition. Furthermore environmental, structural and mechanical building performance, as well as cultural, historical and architectural values, style and age are vital to the understanding of the current state of the building. These information is necessary for further analysis allowing the understanding of the necessary actions to intervene.

Accurate and up to date information information can be generated through ADP and TLS surveys. The final product of ADP and TLS are the point clouds, which can be used to complement each other. The

combination of these techniques with traditional RTS survey provide an accurate and up to date base that, along with other existing information, allow the planning of building interventions.

As-built BIM adoption problems refer mainly to the analysis and generation of building geometry, which usually is a previous step to the link of non-geometric building information. For this reason the present thesis focus mainly in finding guidelines to decrease the difficulty in generating the as-built-BIMs elements.

To handle uncertain data and unclear or hidden semantic information, one can complement the original data with additional missing information. The workflows in the present thesis address mainly the missing visible information. In the case of refurbishment projects the hidden information can be acquired to some extend with ADP or TLS surveys after demolition of some elements and wall layers. This allows a better understanding of the non visible materials layers of a building element whenever it is a partial demolition. This process is only useful if a part of the element material is removed, it can not be applied to the non intervened elements. The handling of visible missing data, objects and relations can be done by integrating different kind of data from different kind of sources. Workflows to connect them in a more integrated way should be implemented. Different workflows can create additional missing information, used to complement or as a base for decision making when no data is available. Relating to adding missing data through point cloud data generation the study cases outlined the importance of planning the survey, with all parts understanding what the project needs are. In addition to accuracy, the level of interpretation and modelling tolerances, required by the project, must also be agreed and understood. Not all survey tools and methods are suitable for all buildings: the scale, materials and accessibility of building play a major role in the survey planning.

To handle the high modeling/conversion effort one has to understand the current workflows to analyse building geometry. As-built BIMs are majorly manually generated through CAD drawings and/or PCM data. These are used as a geometric basis input from where information is extracted. The information used to plan the building intervention should be checked, confirming it is a representation of the as-is state of the building.

The 3D surveys techniques to capture the as-is state of the building should be integrated in the as-built BIM workflow to capture the building data in which intervention decisions are made. The output of these techniques should be integrated with different kind of data to provide the most accurate and complete basis. The architectural company should have technical skills to know what to ask for and to use it appropriately. Modeling requirements should focus primarily on the content of this process:

what to model, how to develop the elements in the model, what information should the model contain, and how should information in the model be exchanged. The point clouds survey should be done after stipulating the project goal, standards, tolerances and modeling content.

Tolerances and modeling guidelines change across companies and countries. Regardless of these differences the standards documents have the purpose of producing and receiving information in a consistent data format, in efficient exchange workflows between project stakeholders. The critical thinking of the modeling workflow and, the communication and agreement between all parts involved in the project, is the prime product of this thesis guidelines. The establishment and agreement of modeling tolerances and the level of development and detail present in the BIMs, between the different parts involved on the project, is more important than which of the existing definitions currently in use by the AEC industry is chosen. Automated or semi-automated tools for elements shape extraction, elimination or reduction of repetitive tasks during the BIMs development and, analysis of environment or scenario conditions are also a way of decreasing the modeling effort.

One of the reasons why standards are needed is the structure and improvement of the collaboration not only with outside parts but also inside architectural offices. Data and workflow standards are very hard to implement daily, in a practical way, resulting in confusing data and workflows. These reduce the quality of communication and project outputs. As-built BIM standards, exactly like BIM standards, contribute to the creation of reliable and useful information.

To update a BIMs during the building life-cycle, one needs to acquire the as-is building state information. Monitoring data, whether consisted by photos, PCM, sensor data, or data resulting from the comparison of PCM and BIMs can be a way of updating existing BIMs. It allows adding continuously information, documenting the building evolution and story, and evaluating possible prevention interventions for its enhancement.

BIM environments are not often used to document existing buildings or interventions in existing buildings. The authors propose to improve the situation by using BIM standards and/or guidelines, and the authors give an initial overview of components that should be included in such a standard and/or guideline.

Keywords: BIM, Existing buildings, Point clouds, workflows, guidelines

Resumo

As metodologias associadas ao software BIM (Building Information Modeling) representam nos dias de hoje um dos sistemas integrados mais utilizado para a construção de novos edifícios. Ao usar BIM no desenvolvimento de projetos, a colaboração entre os diferentes intervenientes num projeto de arquitetura, engenharia e construção, melhora de um modo muito significativo. Esta tecnologia também pode ser aplicada para intervenções em edifícios existentes. Na presente tese pretende-se melhorar os processos de registo, documentação e gestão da informação, recorrendo a ferramentas BIM para estabelecer um conjunto de diretrizes de fluxo de trabalho, para modelar de forma eficiente as estruturas existentes a partir de nuvens de pontos, complementados com outros métodos apropriados.

Há vários desafios que impedem a adoção do software BIM para o planeamento de intervenções em edifícios existentes. Volk et al. (2014) indica que os principais obstáculos de adoção BIM são o esforço de modelação/conversão dos elementos do edifício captados em objetos BIM, a dificuldade em actualizar informação em BIM e as dificuldades em lidar com as incertezas associadas a dados, objetos e relações que ocorrem em edifícios existentes. A partir desta análise, foram desenvolvidas algumas diretrizes de fluxo de trabalho BIM para modelação de edifícios existentes. As propostas indicadas para as diretrizes BIM em edifícios existentes, incluem tolerâncias e standards para modelar elementos de edifícios existentes. Tal metodologia permite que as partes interessadas tenham um entendimento e um acordo sobre o que é suposto ser modelado. Na presente tese, foi investigado um conjunto de tópicos de pesquisa que foram formuladas e colocadas, enquadrando os diferentes obstáculos e direcionando o foco de pesquisa segundo quatro vectores fundamentais:

1. Os diferentes tipos de dados de um edifício que podem ser adquiridos a partir de nuvens de pontos;
2. Os diferentes tipos de análise de edifícios;
3. A utilização de standards e BIM para edifícios existentes;
4. Fluxos de trabalho BIM para edifícios existentes e diretrizes para ateliers de arquitectura.

A partir da pesquisa efetuada, pode-se concluir que é há necessidade de uma melhor utilização da informação na tomada de decisão no âmbito de um projeto de intervenção arquitetónica. Diferentes tipos de dados, não apenas geométricos, são necessários como base para a análise dos edifícios. Os dados não geométricos podem referir-se a características físicas do tecido construído, tais como materiais, aparência e condição. Além disso, o desempenho ambiental, estrutural e mecânico de um edifício, bem como valores culturais, históricos e arquitetónicos, essenciais para a compreensão do

seu estado atual. Estas informações são fundamentais para uma análise mais profunda que permita a compreensão das ações de intervenção que são necessárias no edifício.

Através de tecnologias Fotogrametria (ADP) e Laser Scanning (TLS), pode ser gerada informação precisa e actual. O produto final da ADP e TLS são nuvens de pontos, que podem ser usadas de forma complementar. A combinação destas técnicas com o levantamento tradicional Robotic Total Station (RTS) fornece uma base de dados exata que, juntamente com outras informações existentes, permitem o planeamento adequado da intervenção.

Os problemas de utilização de BIM para intervenção em edifícios existentes referem-se principalmente à análise e criação de geometria do edifício, o que geralmente é uma etapa prévia para a conexão de informação não-geométrica de edifícios. Por esta razão, a presente tese centra-se principalmente na busca de diretrizes para diminuir a dificuldade em criar os elementos necessários para o BIMs.

Para tratar dados incertos e pouco claros ou informações semânticas não visíveis, pode-se complementar os dados originais com informação adicional. Os fluxos de trabalho apresentados na presente tese focam-se principalmente na falta de informação visível. No caso de projetos de remodelação, a informação não visível pode ser adquirida de forma limitada através de levantamentos ADP ou TLS após a demolição de alguns elementos e/ou camadas de parede. Tal metodologia permite um melhor entendimento das camadas de materiais não visíveis dos elementos do edifício, quando a intervenção é uma demolição parcial. Este processo é útil apenas se uma parte do material do elemento é removida e não pode ser aplicada a elementos não intervencionados. O tratamento da informação em falta pode ser feito através da integração de diferentes tipos de dados com diferentes origens. Devem ser implementados os fluxos de trabalho para a integração da informação. Diferentes fluxos de trabalho podem criar informação em falta, usada como complemento ou como base para a tomada de decisão quando não há dados disponíveis. Relativamente à adição de dados em falta através da geração de nuvem de pontos, os casos de estudo destacam a importância de planear o levantamento, fazendo com que todas as partes compreendam as necessidades associadas ao projeto. Além da precisão, o nível de tolerância de interpretação e modelação, requeridos pelo projeto, também devem ser acordados e entendidos. Nem todas as ferramentas e métodos de pesquisa são adequados para todos os edifícios. A escala, os materiais e a acessibilidade do edifício desempenham um papel importante no planeamento do levantamento.

Para lidar com o elevado esforço de modelação, é necessário entender os fluxos de trabalho necessários para analisar a geometria dos elementos do edifício. Os BIMs construídos são normalmente gerados manualmente através de desenhos CAD e/ou nuvens de pontos. Estes são usados como base geométrica a partir da qual a informação é extraída. A informação utilizada para planear a intervenção do edifício deve ser verificada, confirmando se é uma representação do estado actual do edifício.

As técnicas de levantamento 3D para capturar a condição atual do edifício devem ser integradas no fluxo de trabalho BIM, construído para capturar os dados do edifício sobre os quais serão feitas as decisões de intervenção. O resultado destas técnicas deve ser integrado com diferentes tipos de dados para fornecer uma base mais precisa e completa. O atelier de arquitetura deve estar habilitado com competências técnicas adequadas para saber o que pedir e o que utilizar da forma mais adequada. Os requisitos de modelação devem concentrar-se principalmente no conteúdo deste processo, ou seja, o que modelar, como desenvolver os elementos no modelo, quais as informações que o modelo deve conter e como deve ocorrer a troca de informações no modelo. O levantamento das nuvens de pontos deve ser efectuado após ter sido estipulado o objetivo do projeto, standards, tolerâncias e tipo de conteúdo na modelação.

As tolerâncias e normas de modelação são diferentes entre empresas e países. Independentemente destas diferenças, os documentos standard têm como objetivo produzir e receber informação num formato de dados consistente e em fluxos de trabalho de troca eficiente entre os diferentes intervenientes do projeto. O pensamento crítico do fluxo de trabalho de modelação e a comunicação e acordo entre todas os intervenientes são os principais objetivos das diretrizes apresentadas nesta tese. O estabelecimento e o acordo de tolerâncias de modelação e o nível de desenvolvimento e detalhes presentes nas BIMs, entre as diferentes partes envolvidas no projeto, são mais importantes do que as definições existentes atualmente e que são utilizadas pela indústria da AEC. As ferramentas automáticas ou semi-automáticas para extração da forma geométrica, eliminação ou redução de tarefas repetitivas durante o desenvolvimento de BIMs e a análise de condições de ambiente ou de cenários, são também um processo de diminuição do esforço de modelação.

Uma das razões que justifica a necessidade de standards é a estrutura e a melhoria da colaboração, não só para os intervenientes fora da empresa, mas também dentro dos ateliers de arquitetura. Os dados e standards de fluxo de trabalho são difíceis de implementar diariamente de forma eficiente, resultando muitas vezes em dados e fluxos de trabalho confusos. Quando tal situação ocorre, a qualidade dos resultados do projeto reduz-se e pode ficar comprometida. As normas aplicadas aos BIMs construídos, exatamente como as normas aplicadas aos BIMs para edifícios novos, contribuem para a criação de informação credível e útil.

Para atualizar um BIMs durante o ciclo de vida de um edifício,é necessário adquirir a informação sobre o estado actual do edifício. A monitorização de dados pode ser composta por fotografias, PCM, dados de sensores, ou dados resultantes da comparação de PCM e BIMs e podem representar uma maneira de atualizar BIMs existentes. Isto permite adicionar continuamente informações, documentando a evolução e a história da construção e possibilita avaliar possíveis intervenções de prevenção para a sua valorização.

BIM não é geralmente usado para documentar edifícios existentes ou intervenções em edifícios existentes. No presente trabalho propõe-se melhorar tal situação usando standards e/ou diretrizes BIM e apresentar uma visão inicial e geral dos componentes que devem ser incluídos em tais standards e/ou linhas de orientação.

Palavras-chave: BIM, Edifícios existentes, nuvens de pontos, fluxos de trabalho, diretrizes

1
Introduction

1.1 As-built BIM

Recently, planning and implementing rehabilitation measures in existing building gained great relevance. Volk et al. (2014, p.111), based in Economidou et al. (2011), states that “in Europe more than 80% of residential buildings are built before 1990” and that the majority of them doesn’t have BIM documentation. Most of these buildings are deteriorating steadily. Hence, efficient and well-considered planning of interventions in these existing buildings (renovation, refurbishment, rehabilitation) is of key importance if we want to keep our building stock of an appropriately high quality. Vainio (2011) points out that several aspects of planning interventions in existing buildings need improvement, including the know-how of specialists and cooperation between specialists. Some of these aspects can be improved through an implementation of new technologies. Such technologies might avoid conflicts, time wasting reworks and their consequent costs (Vainio, 2011).

Interventions in existing buildings can assume different shapes. We consider three kinds of major interventions: restoration, rehabilitation, and refurbishment of buildings. Genovese (2005) defines restoration as a set of actions oriented to preserve the architectural, artistic, historical and structural objects characteristics and values; preventing and controlling the materials degradation. According to Mateus (2012), based on Pereira (2003), rehabilitation corresponds to a series of actions aiming to increase the quality levels of a building so that it fits the higher performance standards. It may include significant changes to the building, even demolition of some parts. Refurbishment interventions correspond to the series of actions intended to extend the useful life of existing buildings through the adaptation of their basic forms, resulting in a new or updated version of the original structure (Riley & Cotgrave 2011). This adaptation can lead to new uses and significant transformation of the building logic but does not include major structural alterations like Rehabilitation (Douglas 2006).

During any of these three types of interventions, the building needs to be understood in all its facets: its material, cultural and temporal values. To obtain this understanding, it is necessary to gather updated and accurate building data that can be interpreted by the different specialists involved in the project. The processes to acquire the data can be technologies like Terrestrial Laser Scanning (TLS) surveys and Automated Digital Photogrammetry (ADP). The output of these surveys, the point clouds, can be integrated with Building Information Modeling authoring tools, used for the management of data. Hence, the information can be more easily managed and exchanged, ideally allowing a more integrated and cohesive building intervention.

The present thesis researches Building Information Modeling (BIM) processes for interventions in existing building by architectural offices. The thesis outlines the data capture (survey techniques) and data analysis (data interpretation and management) needed for the creation and development of the building information model (BIMs).

The main objective of this research is to improve the processes of recording, documenting and management of as-built information. A set of workflows will be established to incorporate all relevant related data in an information system. In other words, a methodology to efficiently model an existing structure in BIM from the integrated products of terrestrial laser scanning and automatic digital photogrammetry complemented with any other appropriate methods. This methodology is proposed after an in-depth investigation of existing workflows and technologies. The workflows described and evaluated are real-world projects, developed during research and daily work at ArcHC_3D research group[1], Dark Arkitekter[2], The Beck Group[3] and Grape Architects[4]. The projects analysed are: Belém Palace survey from ArcHC_3D research group at FA-ULisboa; Ruseløkkveien, Akersgata and Karl Johans Gate 8-10 from Dark Arkitekters;. El Jebel, Medica Sur, College Station Theater and Trinity forest survey from The Beck Group; and Briskebyveien 38, Sognsveien 9A and Vitusapotek Volvat study from Grape Architects.

This research focuses on: i) the building data acquisition and processing, ii) the building data analysis and, iii) the BIM workflows, for existing buildings intervention, by architectural offices. Hence these processes will be described and evaluated for the above projects and surveys.

The application of BIM processes have primarily been developed for the planning, design, construction and integrated project delivery phases of new buildings. Nonetheless, its features can be successfully applied to existing facilities as well, allowing improvements in their maintenance, refurbishment and

[1] http://archc3d.fa.ulisboa.pt/index.html
[2] http://darkarkitekter.no/
[3] http://www.beckgroup.com/
[4] http://grape.no/

deconstruction (Garagnani & Manferdini 2013). Volk et al. (2014) outlined the major benefits of BIM usage, namely design consistency and visualization, cost estimation, clash detections, accurate information management and, stakeholder collaboration improvement. It is also pointed out the potential benefits of using BIM for planning interventions in existing buildings. These benefits include assessment and monitoring, structured up-to-date information that reduces errors and financial risk, cost calculation, quality control, and retrofit planning.

Many existing buildings have insufficient documentation attributed to omitted updates, and obsolete, or incomplete information, which limits BIM processes. For this reason, we consider the combined usage of BIM and new survey technologies, namely 3d laser scanning and digital photogrammetry, is essential to provide a reliable and accurate data basis from which a building intervention can be developed.

1.2. Research questions

The integration of point cloud data, acquired by laser scanning and/or digital photogrammetry, in BIM systems, can be complemented or not with other surveying methods. The application of these processes, for the as-built environment, is a way to strengthen and to enhance the efficiency of the building information usage. We will therefore look into the following research question:
How to combine point cloud data with BIM processes in order to generate an efficient model for planning interventions in existing buildings?

This main question can be further subdivided:
1. What kind of data is needed to describe the current state of a building?
2. What kind of data can be extracted from 3D point clouds?
3. What are the limitations of point cloud data and how to overcome them?
4. How can data and its analysis, regarding existing buildings, be processed in BIM tools?
5. How can standards contribute to as-built BIM workflows efficiency?
6. How to handle and model uncertain data?
7. What other techniques and methods can be used to gather more information?
8. How to minimize the high modeling effort of existing buildings in BIM?
9. How to maintain the BIMs?

Through these research questions, this thesis will work towards guidelines for methodological workflows to integrate BIM tools and point cloud data efficiently for planning interventions in existing buildings. The comparison of the results obtained with various projects were achieved through qualitative analysis methods.

1.3. Thesis outline

In this thesis, we will go through a number of chapters. Chapter 1 is the introduction, where the thesis topic motivation, methodologies and research questions are addressed. In Chapter 2 to 3, we will go through a state of the art review of existing building survey techniques, existing building data analysis processes and building information modelling (BIM) technologies. Chapter 4 outlines the state of art of BIM and workflows standardization, and addresses their adoption for existing buildings interventions. Chapter 5 is composed of current workflows (case studies) in which building survey techniques, namely 3D laser scanning and digital photogrammetry, and BIM tools are combined to plan interventions in existing buildings. A critical analysis of the workflows is done in each case study. Chapter 6 gathers what has been learnt from all the preceding chapters in guidelines about the use of 3D survey data and BIM tools workflows. The thesis then concludes in Chapter 7 with the conclusions of the work, how it relates to the questions posed at the beginning and what the key contributions have been from this PhD. Figure 1.1 is a schematic diagram to explain the focus of each Chapter.

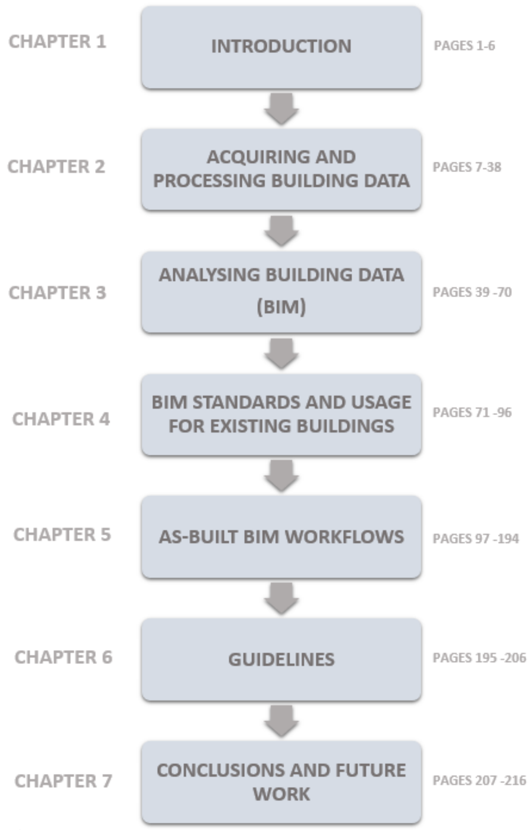


Figure 1.1- Schematic diagram of the Chapters subject sequence

1.4. Thesis Dissemination

1.4.1. Publications

- ❑ (2016) BARBOSA Margarida, PAUWELS Pieter, FERREIRA Victor, MATEUS Luís, "Towards increased BIM usage for existing building interventions", Structural Survey, Vol. 34 Issue: 2, pp.168-190, doi: 10.1108/SS-01-2015-0002 (Award for Excellence - 2017 Outstanding Paper)
- ❑ (2013) MATEUS Luís, FERREIRA Victor, BARBOSA Margarida "An expeditious methodology to correct the closure error of point clouds registration"in the proceedings of the conference SYMCOMP 2013, International Conference on Algebraic and Symbolic Computation, IST, Lisbon. Edited by APMTAC, September 2013, ISBN 978-989-96264-5-4
- ❑ (2012) MATEUS Luís, BRITO Nelson, FERREIRA Victor, BARBOSA Margarida, AGUIAR José; "New tools for visual assessment of building deformations", proceedings of the International Conference on Structural Analysis of Historical Constructions, SAHC 2012, 15-17 October 2012, Wrocklaw, Poland. Vol. 3. pp. 2463-2470. ISBN: 978-83-7125-219-8.
- ❑ (2012) MATEUS Luís, FERREIRA Victor, AGUIAR José, BARBOSA Margarida; "TLS and digital photogrammetry as tools for conservation assessment", proceedings of 3rd International Conference on Heritage and Sustainable Development - Heritage 2012. eBook ISBN: 978-989-95671-8-4. Editors Rogério Amoêda, Sérgio Lira, Cristina Pinheiro. Published by Green Lines Institute.

1.4.2. Presentations

- ❑ Transformasjon og rehabilitering Estate konferansen, Oslo, Norway, December 2016
- ❑ Monitoring and optimizing AEC & BIM processes through Reality Capture, RTC EUR 2016 Conference, Porto, Portugal, 2016 - 7th place on the top 10 speakers
- ❑ Comparing 3D Approaches and Workflows for Architectural Projects, SPAR3D Expo & Conference, Houston, USA, 2016
- ❑ Using Photogrammetric surveys at Architectural Offices, RTC EUR 2015 Conference, Budapest, Hungary, 2015 - 5th place on the top 10 speakers
- ❑ The use of 3D surveying techniques and BIM for existing buildings intervention, ISEL Seminar, Maintenance Engineering Master, 2014
- ❑ BIM and Rehabilitation session in the Rehabilitation Week of Lisbon - RICS, 2014
- ❑ An expeditious methodology to correct the closure error of point clouds SYMCOMP 2013,

International Conference on Algebraic and Symbolic Computation, IST, Lisbon, 2013

- BIM and Point Clouds on Architectural Rehabilitation, Ist BIM INTERNATIONAL CONFERENCE, Porto,2013
- BIM and Heritage, BIM IST Seminar- Challenges and Opportunities, Lisbon, 2013
- Strategies for 3D modeling of architectural contexts as supporting information to conservation project - III International Seminar ArcHC_3D, Portugal, January 31, 2011.

2

Acquiring and Processing Building Data

This chapter focuses on the data on which intervention decisions are based. Section 2.1 will outline the need to have more accurate and reliable building information when intervening in a building. Section 2.2 then focuses on what data can be obtained using traditional tools. Section 2.3 gives an overview of how the existing information can be complemented and improved with 3D surveying techniques, like Automated Digital Photogrammetry (ADP) and Terrestrial Laser Scanning (TLS) techniques. Section 2.3.1 describes their output data, the point clouds, while Section 2.3.2 and 2.3.3 will approach them separately, describing the acquisition and processing processes. After this, Section 2.3.4 outlines the strengths of both techniques, comparing them. Section 2.4 focus on point clouds, particularly in the information that can be extracted from them and in their limitations. Figure 2.1 is a schematic diagram to explain the focus of each Section in chapter 2.

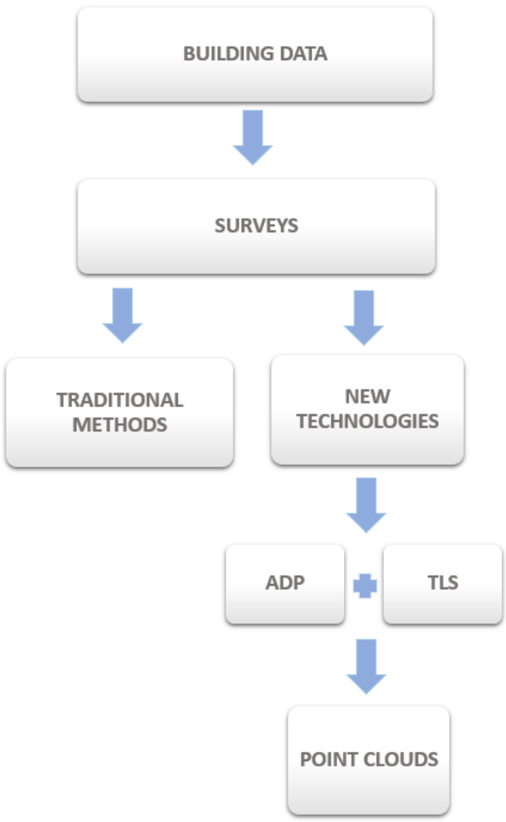


Figure 2.1- Schematic diagram of the Section 2 subject sequence

2.1. The need for better documentation for interventions in existing buildings

Recent emphasis on adaptive reuse of buildings, especially in light of the current economic climate and sustainability efforts, is a trend that has increasingly become stronger. The main reasons to intervene in existing buildings are defined by Paiva et al. (2006): i) Structural and physical degradation due to age, pollution, climatic exposition, road traffic vibration, and lack of maintenance; ii) Inadequacy of function, security, comfort, habitability, sustainability, and healthy conditions; iii) Non adequacy for the current legal building conditions.

Once one needs to intervene in a building, the intervention usually consists of four main phases (Paiva et al. 2006): i) Methodology and scheduling of the intervention; building characteristics study; ii) Information and documentation, gathering information from several areas; iii) Analysis and diagnose of the state of the object, definition of rehabilitation aims and its priorities; iv) Measures and solutions.

Studies that justify and support intervention decisions are of vital importance. In order to plan a series of actions to intervene in an existing reality, it is necessary to know and characterize it. This is partly done through a careful survey of the built environment as it is built (as-built survey). The as-built survey allows the specialist to identify, analyze, and record the origin of a building, as well as the transformations suffered, and the evolution of its construction from the initial form to the current state.

Different kind of data, not just geometric, is needed for the analysis of the current building state. Non-geometric information can refer to physical characteristics of the built fabric, such as materials, appearance and condition. These also include building elements deformation and material deterioration, among others. In addition, environmental, structural and mechanical building performance, as well as cultural, historical and architectural values, are vital to the understanding of the current state of the building. This information allows the analysis and understanding of the necessary actions to intervene in a building.

One can interpret and analyze building data based on a strict methodology that records a wide range of information and describes the as-built environment in its geometrical, constructive, functional and spatial aspects (Docci 2005). This information can consist of simple hand notes, photos, hand drawings, CAD drawings, manual hand measures, audio recordings, movies, etc. This is the data obtained by traditional methods that will be discussed in Section 2.2. This thesis research is based on our experience of the general use of information for existing buildings intervention projects in architectural offices.

The initial building information usually consists of photos, hand drawings, web maps and images obtained from it. Also CAD plans, elevations and sections of the object in study are often used, as they are normally generated to plan the building construction. This information is actually a valuable source for the building study, but one cannot start intervening in a building assuming this is a static object and that all previous interventions were accurately registered to the millimeter in available documentation. A building is connected to a site that is in constant movement, earth is in constant mutation. This will make the elements of the building adapt and move through the years. Also the building users will not only wear it out but they might make unregistered changes. Another important point to consider is that the original project rarely corresponds to what is constructed. This is why, in our experience, this data is often considered to be insufficient or inappropriately used for the intervention planning if not checked. It should be improved and complemented with more reliable and accurate information (see Section 2.3). The photos, hand drawings and plans, CAD drawings are usually not integrated in an efficient workflow to exchange information and this can also generate loss of information or be an insufficient base for decisions.

Furthermore, architectural offices seldom have many resources and building measures are often manually acquired with a tape measure or an electronic distancing meter device. This can be a source of unreliable and inaccurate data. Even when there is a methodological measurement (like doing it several times and obtaining the main measure), the information obtained will differ between different users. Besides the measures accuracy issue, they are also discrete measures, which means they capture some selected elements features, and as the captured detail increases also the time spent grows. This is why it is affirmed that there is need for better documentation and methodologies in existing building intervention projects, not only in the data survey methods but also in the data usage.

The data above described focus more on the geometry studies of the building. Data for deformation/deviation studies, materials condition state, human comfort conditions studies and studies of environmental conditions are also essential to describe the state of the building and should be used for planning the intervention.

The data used for building intervention planning can be improved in the following key points:

- ❏ The existing information should be checked, understanding if it is accurate and up to date, otherwise should be used as historical document not as a base for intervention
- ❏ Different kinds of data, not just geometric, are needed as base for the analysis of the current building state. Examples can be data for the analysis of the material state and deformation, among others.
- ❏ Different kind of data should be used to complement each other. Workflows to connect them in a more integrated way should be implemented.

2.2. Traditional methods for surveying

Traditional survey methods consist not only of hand notes, metric tape measurements, photos, hand drawings, audio recordings, movies; but also of computer-aided manual surveying methods, GPS positioning, and total stations (classic topographic surveying). In these methods, each point of the object under recording is carefully chosen and recorded in the field. In practice, a small amount of points are selected and recorded to correctly depict the object.

2.2.1. Robotic Total Station (RTS)

The first Robotic Total Station (RTS) was Geodimeter 500 (Trimble) and was created in 1990 (Cheves, 2007). The RTS combines the angle measuring capabilities of theodolite with an Electronic Distance Measurement (EDM) to determine the horizontal and vertical angle, and slope distance to a point. An RTS can acquire the coordinates of an unknown point relative to a known coordinate, as long as a direct line of sight can be established between the two points. Angles and distances are measured from the RTS to points under survey, and the coordinates (X, Y, and Z) of the points (relative to the RTS) are determined using trigonometry and triangulation. Reflectorless RTS technologies enable the measurement of distances of up to hundreds of meters without needing to access the target. Inaccessible objects or objects located at dangerous sites can thus be easily mapped. The building is surveyed by obtaining key points from which plans, section and elevations are made.

2.2.2 Computer-aided manual surveying (CAMS)

CAMS consists of Electronic Distance Measurement (EDM) devices, whose evolution is described in Cheder (2207). They are simple and cost effective means of quickly measuring simple geometric dimensions. The measurements are taken in direct contact with the building. Dimensions are measured between two surfaces (wall length, room height, and so on), which can be seen from one another. This kind of device is used in most architectural offices to acquire the building rooms dimensions that will complement existing information. It is usually used to extract few measurements to check the quality of existing information or sometimes to control scale.

Traditional survey techniques, like RTS, are used to establish primary control and to provide an accurate geometrical framework for a building project. Architectural offices usually outsource the survey control framework, either to obtain the entire building control survey or to complement the information they already have. For example, one can add georeferenced points to existing points in a plan with null origin point. These techniques are usually present in bigger projects. On smaller projects like apartments or small interventions usually the architect uses the CAMS associated with hand notes and photos. It is not justified most of cases the use of RTS on these projects.

2.3. New technologies for surveying - 3D Surveys

RTS surveys acquire point by point which means it will take a lot of time and consequently money to do it. New survey techniques, such as Terrestrial Laser Scanning (TLS) and Automatic Digital Photogrammetry (ADP), can rapidly and accurately capture and measure the as-built environment. The TLS and ADP methods capture everything that is visible and allow to verify later the measures or capture some needed detail that was missing from the initial model. These new technologies can complement and very often replace the traditional methods. Some of these methods have been adopted in the industry for some time. It was in 2008, when the General Assembly of the International Society of Photogrammetry and Remote Sensing[5] (ISPRS 2008) outlined the need to develop innovative technologies and products to support archaeological, architectural and conservation activities through the use of 3D modeling, virtual reality and animation. The London charter for the computer-based visualization of cultural heritage (2009)[6] also supported the use of new technologies for existing buildings, in the case of heritage, stating:

1. The adoption of the forms of computer visualization can be technically and intellectually as accurate as other techniques, and this form of documentation is an asset allowing access to a type of information not feasible by other means. However, one ought not to always assume that this is the most appropriate strategy.

[5] Non-governmental organization focused on the development of international cooperation for the progression of photogrammetry and remote sensing.
[6] http://www.londoncharter.org/fileadmin/templates/main/docs/london_charter_2_1_en.pdf

2. The documentation strategies should consider mechanisms for evaluation and comparison of the various modes adopted in order to detect any problems and limitations.
3. The documentary method should be as comprehensive as possible, being characterized like its real-world counterpart.

Most commonly outlined 3D survey techniques are Automatic Digital Photogrammetry (ADP) and Terrestrial Laser Scanning (TLS). These methods have no contact with the object in study and points are recorded indistinguishably. In practice, a large amount of points are recorded and point selection, if done, is accomplished later in the office.

Both ADP and TLS are subdivided into two main steps: the acquisition of the data and processing of the data into structured information of the data (Figure 2.2). The result of the 3D survey on site is either a set of point clouds or a set of images from which point clouds can be generated

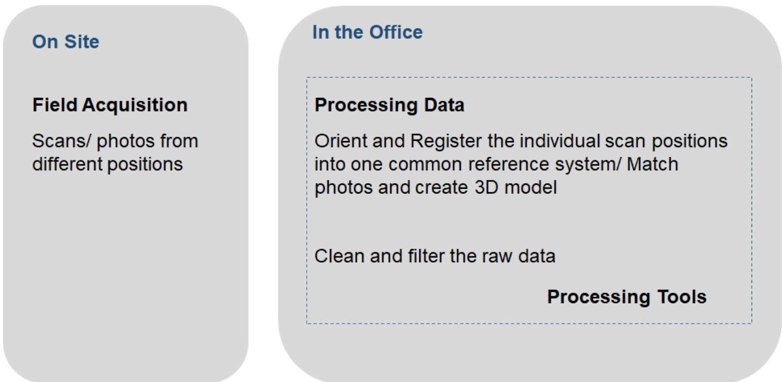


Figure 2.2-ADP and TLS are subdivided into two main steps: the acquisition and the processing of the data

2.3.1. Point clouds

3D point clouds represent the first possible product of the TLS and TDP survey. In a 3D point cloud, each point can be represented by spatial Cartesian coordinates (x,y,z), RGB colors (r,g,b,), normal vectors (nx,ny,nz) and, in the TLS case, reflected intensity of the laser light (Amaral et al. 2013), or any other components associated with the points in space. These 3D point clouds are unlikely to be considered final products. This means that further processing is always needed to have something which we can call a model.

The first thing we can call a 3D model is a set of oriented point clouds with a proper scale and orientation defined, with some kind of radiometric information associated and with spurious data removed. We refer to this as a point cloud model (PCM). Basically, a PCM is a large set of points in three-dimensional space with known coordinates in a given reference frame, that visually describes an object almost in a continuous way. In Figure 2.3 we can observe individual point clouds represented with different colors registered and oriented to the same reference system. In the right image the point clouds color information is substituted by RGB colors.

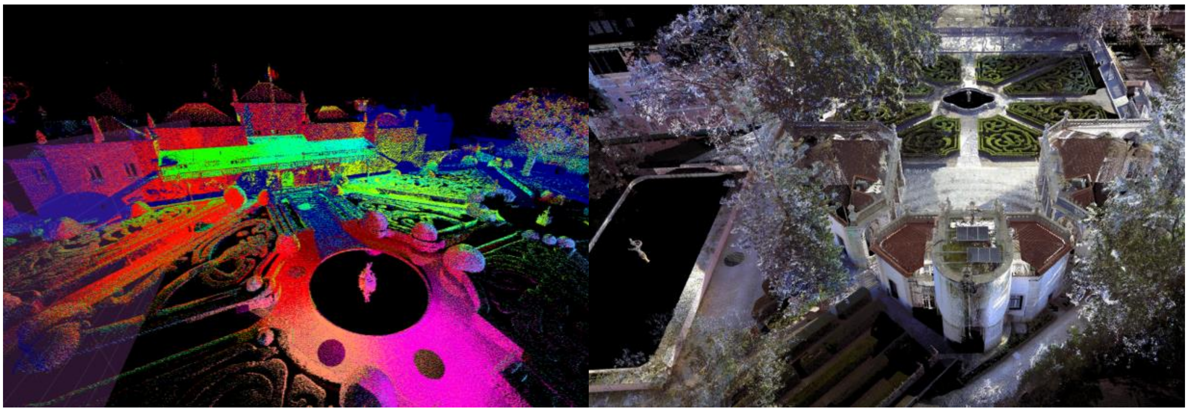
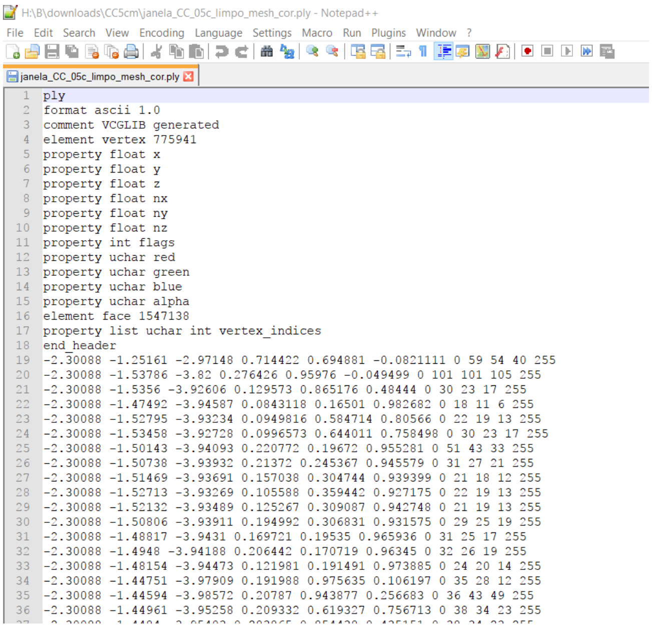


Figure 2.3 -Belém palace PCM: left image: each point clouds has one color;right image: PCM points colored by RGB color. Source:image courtesy ArcHC_3D

These 3D models are processed with specific software tools that enable the user to perform several operations such as cleaning of unwanted points (like reflection points and too distant points), registering, segmentation, meshing, etc. Each individual point cloud consists basically in a set of points each of which is represented as vector with n coordinates depending on the data associated with the points. These can be stored in several formats with different levels of compression. A very common format is the PLY ASCII format as we can see in the Figure 2.4. The advantage of this format is that it can be directly read by humans because it is a simple text file. The disadvantage is the big size of the files because there is no compression.

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comment VCGLIB generated
element vertex 775941
property float x
property float y
property float z
property float nx
property float ny
property float nz
property int flags
property uchar red
property uchar green
property uchar blue
property uchar alpha
element face 1547138
property list uchar int vertex_indices
end_header
-2.30088 -1.25161 -2.97148 0.714422 0.694881 -0.0821111 0 59 54 40 255
-2.30088 -1.53786 -3.82 0.276426 0.95976 -0.049499 0 101 101 105 255
-2.30088 -1.5356 -3.92606 0.129573 0.865176 0.48444 0 30 23 17 255
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-2.30088 -1.50738 -3.93932 0.21372 0.245367 0.945579 0 31 27 21 255
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-2.30088 -1.48154 -3.94473 0.121981 0.191491 0.973885 0 24 20 14 255
-2.30088 -1.44751 -3.97909 0.191988 0.975635 0.106197 0 35 28 12 255
-2.30088 -1.44594 -3.98572 0.20787 0.943877 0.256683 0 36 43 49 255
-2.30088 -1.44961 -3.95258 0.209332 0.619327 0.756713 0 38 34 23 255
```

Figure 2.4 - Image of what is Point cloud file

Data can be exported in closed proprietary formats that are created by proprietary software (belonging to a company) and are just read by the corresponding software, or can be exported in open formats, which can be read by different software, both proprietary and free open-source software[7]. Closed file formats vary according to the different settings of different brands of scanners and software companies.

As examples of open formats, it can be point out:

- PLY - a polygon file format, developed at Stanford University
- STL - a file format native to the stereolithography CAD software created by 3D Systems
- OBJ - a geometry definition file format first developed by Wavefront Technologies
- X3D - the ISO standard XML-based file format for representing 3D computer graphics data
- Other formats: ASC, CL3, CLR, E57, FLS, FWS, ISPROJ, LAS, PCG, PTG, PTS, PTX, RDS (3D only), TXT, XYB, XYZ, ZFS, ZFPRJ.

These file formats correspond to raw data files. In order to insert PCM into data management software, more generally considered BIM software, these formats need, sometimes, to be converted into proprietary files. This allows the software to deal with it in a more efficient and faster way.

Autodesk® Revit® software supports RCS and RCP. In RCS a single point cloud file is saved in the Output folder after indexing, using meter as the unit of measurement. RCP is a project file that points to the individual RCS files and contains information about them. *Archicad* software supports the .E57 and .XYZ point cloud file formats. These different formats of information extracted from point clouds allow analyzes of existing objects exactly as they were at the moment of the survey. They enable an evaluation of the conformity between the existing structure and a possible ideal structure. And they also support the understanding of the technical and scientific knowledge of the time when the object was constructed (Mateus et al. 2012; Docci 2005). Its disadvantages are the huge data amount and the unwanted noise points, its high computational requirements and workers skills, leading to greater costs.

[7] https://en.wikipedia.org/wiki/Open_format

2.3.2 Automatic Digital Photogrammetry (ADP)

ADP is the technique that allows to accurately relate the geometrical information of an object with digital images through measurements performed on those images (Bethel et al. 2001; Mateus 2012). These processes are based on structure from motion (SFM) principle, or equivalent, and combined with multi-view-stereo (MVS), or equivalent, for dense reconstructions (Vosselman & Maas 2010; Mateus 2012). SFM means that the three dimensional structure of image acquisition, including camera parameters estimation, can be automatically recovered from a data set of images with small base distance in between the images (Mateus 2012).

The present research focus on the terrestrial photogrammetry, with imagery taken with hand held cameras or with low altitude platforms like masts, balloons or drones (Figure 2.5).

Figure 2.5 -Photogrammetric survey tools

Examples of software for photogrammetry can be the *Visual SFM, Pix4D, Agisoft* and *Autodesk® Recap® 360,* referred in Table 2.1. In this table we can see outlined some of the software differences and the difference between software that generates the PCM from the software that does not generate the points but allows to edit the PCM.

Software	Comments
Pix4d	The user has more control over the process it is not cloud based. It is more expensive.

Autodesk® Remake®	Cloud software, limited to 250 photos, the user can not correct or control the way the software algorithms use the data. Has a better performance with bad photos than for example *Pix4d*. It is very affordable
Visual SFM	No limit of photos but the software is not user friendly and need very sharp data
Autodesk® Recap® 360	Cloud based software, with very limited tools
CloudCompare	Point Cloud Editing Freeware software, limited capability of dealing with big point cloud files
Meshlab	Point Cloud Editing Open source software, limited capability of dealing with big point cloud files

Table 2.1- Photogrammetry software examples

Whether the photogrammetry is obtained with hand held cameras or with low altitude platforms like a mast, their process is similar. The next sequence of figures describe ADP steps through a hand held camera attached to a telescopic mast (15m).

1. **DATA ACQUISITION - digital images**

First, one captures the object through photos (figure 2.6).

Figure 2.6- Convento de Cristo window Photogrammetry Survey-capture (ArcHC_3D survey).

In Figure 2.6 the window was captured by a Canon 1Ds Mark III camera. Collecting 556 photos during 1 day, taken at the same hours so the light (and shadows) where constant (Ferreira *et al ,* 2014).

ADP survey varies according to the number of photos, angle of photos, overlapping, camera resolution (and quality), object size and complexity and, environment conditions. The way in which photos are taken can affect the resulting accuracy of the photogrammetric processing of the point clouds. These overall recommendations should be followed:

- ❑ take sharp photos
- ❑ use ISO100, lower ISO less noise
- ❑ capture photos every 5 degrees
- ❑ continue to take overlapping photos without changing settings between photos
- ❑ no dark and no over exposed surfaces
- ❑ homogeneous\indirect lightning
- ❑ when zoomed-in, there should be as much detail as possible
- ❑ minimum 3 photos from any detail
- ❑ optimize the photo frame to capture all the details needed
- ❑ for sharper images, for handheld camera, use remote controller and a tripod

And these should be avoided:

- ❑ direct sunlight
- ❑ shadows (dark areas)
- ❑ blurry photos
- ❑ moving objects
- ❑ changing camera settings
- ❑ shining objects
- ❑ taking photos from same location
- ❑ crop photos

Measurement errors associated with photogrammetry can be attributed to systematic errors connected with:

- ❑ camera factors, like lens distortion and resolution
- ❑ poor planning of camera network geometry, like the shooting distance, percentage of photo overlaps, number of overlapping photos, camera intersection angles, and angles of incidence that allow 3D reconstruction.

Achievable photogrammetric accuracy level should match up to the desired accuracy level for a particular application.

2. **DATA PROCESSING - image analysis and matching**

Afterwards, the photos are processed with a software, like Visual SFM, Agisoft PhotoScan and my3dscanner, that will correlate images in order to calculate 3D points from image pixels, thus generating point clouds and meshes. Figure 2.7 shows on the left, the points recognition (marked by green color) from the pixels, in *VisualSFM*. On the right image, we can observe a diagram of photos correlation, where the photos are repeated on y axis and x axis and the red color identifies common points between the different photos and consequently pixels.

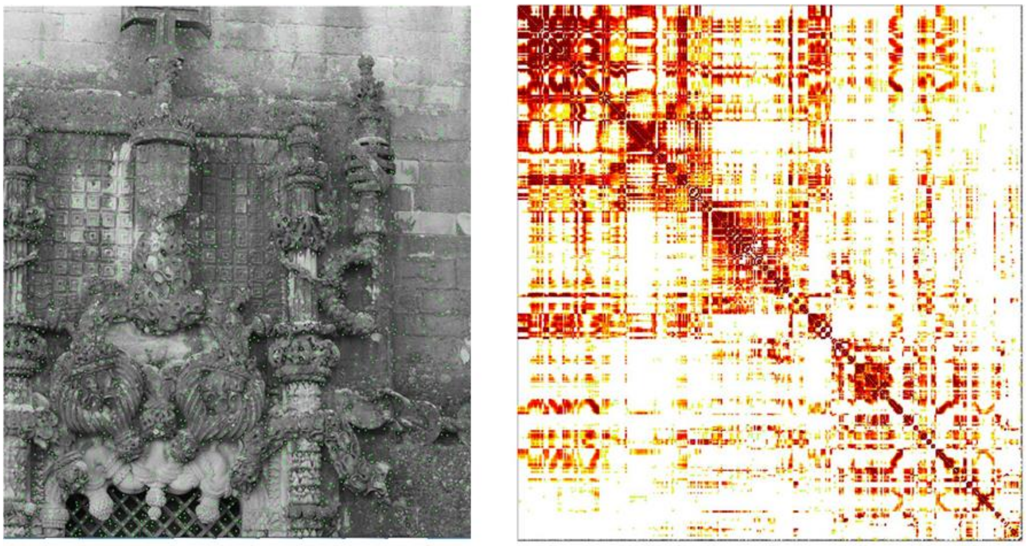


Figure 2.7- Image on the left: *VisualSFM* software correlating 3d points and pixels; image on the right: diagram of photos correlation. Source: Image courtesy ArcHC_3D.

3.**DATA PROCESSING- automatic relative orientation of photos and PCM sparse reconstruction**

Analysing common points and positions between different photos will generate the 3D point cloud model. Figure 2.8 shows the reconstruction, in *VisualSFM*[8], of the relative orientation of the cameras, allowing to project the points in a 3D space.

[8]Developed by Changchang Wu: http://www.cs.washington.edu/homes/ccwu/vsfm/

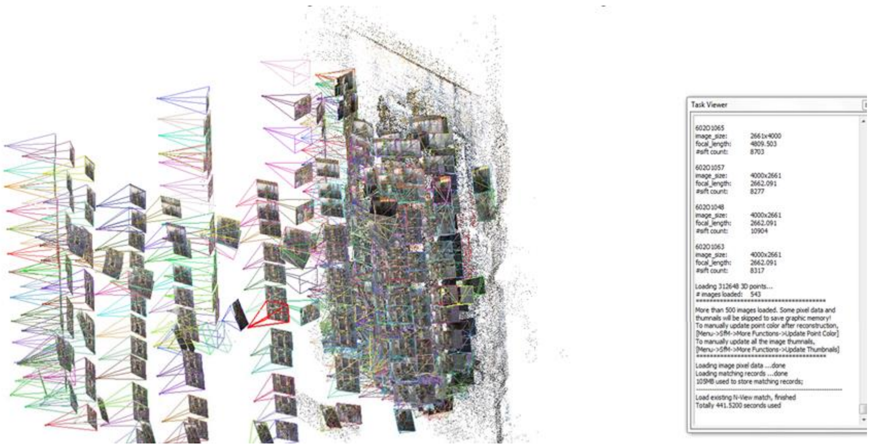


Figure 2.8 - Relative orientation of the cameras.Source: Image courtesy ArcHC_3D

4. DATA PROCESSING - automatic reconstruction of dense point cloud model

Once we have an initial sparse point cloud one can generate a dense point cloud from it. Namely, the number of points is increased. Figure 2.9 shows a dense point cloud. This reconstruction was done with the software CMVS+PMVS[9].

Figure 2.9- ADP dense point cloud. Source: Image courtesy ArcHC_3D

The dense point cloud model was obtained through the sparse one, has more than one point per square millimeter, with approximately 130 million points. Figure 2.10 shows a gradual zoom on this dense point cloud. We can observe from A to C a zoom increase until one can observe the existence of multiple points in just 3cm.

[9]Developed by Yasutaka Furukawa: http://grail.cs.washington.edu/software/cmvs/

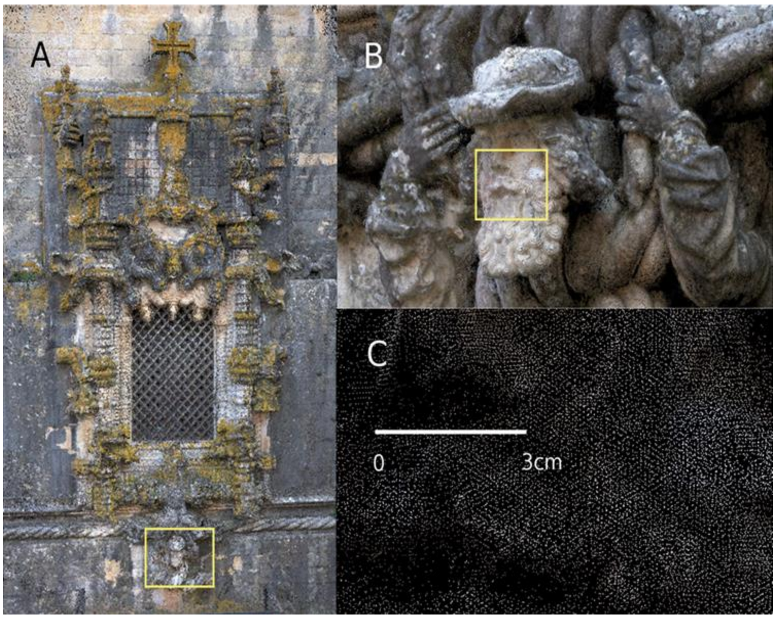


Figure 2.10 - A) Global view of the point cloud model, B) Detailed view, C) Detailed view where point density can be observed. Source: Image courtesy ArcHC_3D

The aerial photogrammetric survey process is similar to the terrestrial, the difference is the tool use to capture the photo from a top view. This tool can be a helium balloon like the one observed in Figure 2.11, from the ADP survey of the “Convento De Cristo” monument, or most commonly drones.

Figure 2.11- Aerial ADP survey through aerial photos of “Convento de Cristo” in Tomar. Source: Image courtesy ArcHC_3D

Survey technologies like laser scanning, can be difficult to execute, in some projects, due to their high cost. Also, considering some large scale or inaccessible areas of a building, it is not always practical to perform traditional measurements. Photogrammetry is generally used to survey simple architectures with regular geometric shapes, small objects with free-form shape, point-based deformation analyses, and low budget terrestrial projects.

2.3.3. Terrestrial Laser Scanning (TLS)

TLS survey consists in the capture of multiple point clouds, by positioning a laser scanning system at various points of view, named stations, concerning the structure under study, recording as much information as possible.

As indicated in the book generated from the the Heritage3D project (English Heritage 2011)[10], laser scanners can be divided in three basic groups concerning to its functioning principle: triangulation, time of flight (TOF) and phase-shift (PS). The technique adopted by triangulation lasers is illustrated in Figure 2.12. Triangulation lasers send a laser pattern onto the object; the beam scatters from the object's surface; and it is finally collected in a point different from the beam projection origin. The projection pattern and the object are measured using plain trigonometry (Mill et al. 2013; Vosselman & Maas 2010). The laser generates a measurement beam that is deflected across the subject by a rotating mirror. The beam is then reflected by the surface of the subject and focused onto the sensor by the lens. The location of the laser pulse on the sensor, plus the known separation (D) between it and the mirror is combined with the recorded angle of the mirror to determine a point coordinate by triangulation.

[10] Historic England, 3D Laser Scanning for Heritage Edition 2, 2011: https://content.historicengland.org.uk/images-books/publications/3d-laser-scanning-heritage2/3D_Laser_Scanning_final_low-res.pdf/

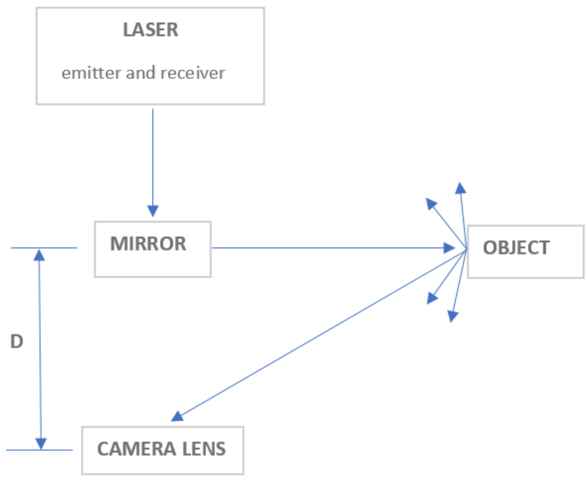


Figure 2.12- A schematic diagram of a mirror-based triangulation measurement system, based in (English Heritage 2011).

TOF lasers are the most often used lasers. They send a pulsed laser beam that is partially reflected by superficies back to the device. The time of this process is measured, and along with the beam speed value and its orientation, we can obtain the distance from the scanner to the object (Amaral et al. 2013; Vosselman & Maas 2010). Figure 2.13 shows a diagram where this process is illustrated.

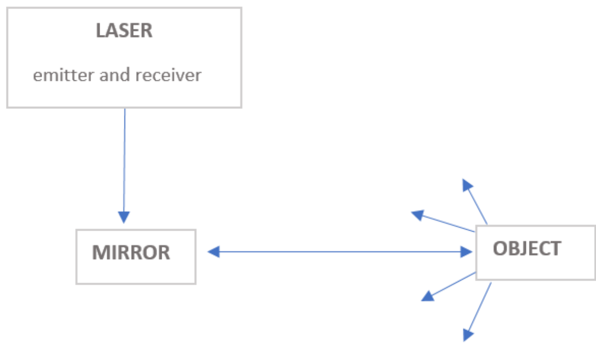


Figure 2.13- schematic diagram of the time-of-flight measurement system, based in (English Heritage 2011).

PS lasers modulate the emitted light laser in amplitude and send it onto surface. The reflection is collected and a circuit measures the phase difference between the sent and received waveforms, this is, the time-delay (Mill et al. 2013; Vosselman & Maas 2010).

To ensure TLS survey accuracy, particularly if the last of the aforementioned options is considered, one should take an approach from the general to the particular, orienting a sequence of point clouds that encloses the boundaries of the area to be recorded, and posteriorly filling out the spaces resulting from it. The line defined by the sequential positions of the origins of the local frames of each point cloud, is given the name of polygonal chain of point clouds. Usually, it is intended that this is a closed line (Figure 2.14).

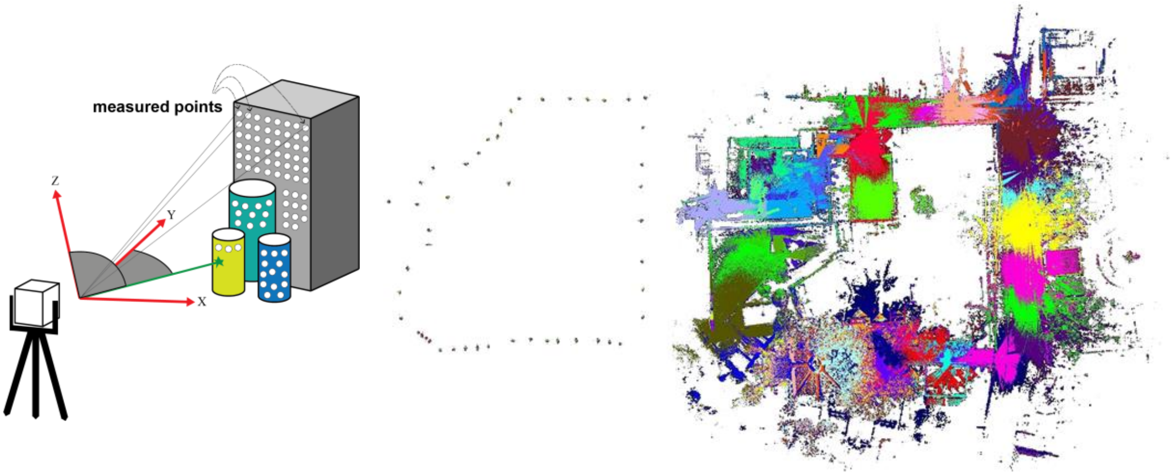


Figure 2.14- Closed polygonal chain of point clouds (left) and oriented point clouds (right).

Relative orientation of the individual TLS point clouds, also called registration, is done through a common coordinate system, local or global, in order to produce a coherent three dimensional model, observed in Figure 2.15. A local reference frame can be defined by the pose of a reference point cloud.

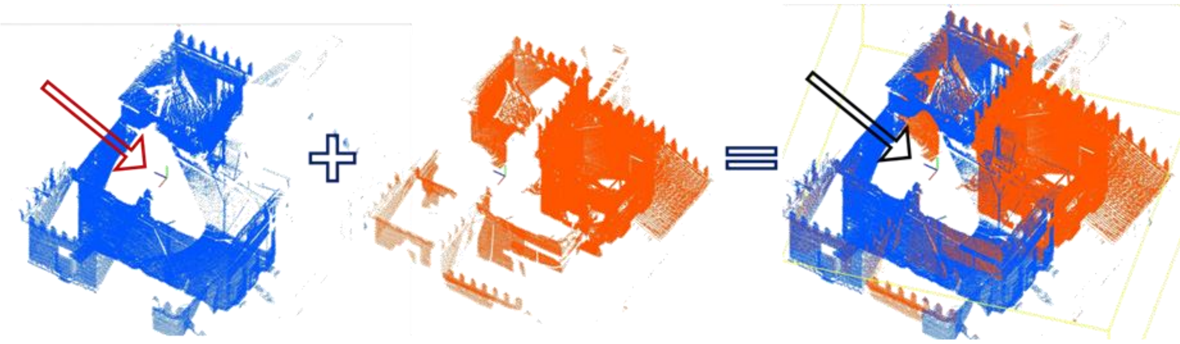


Figure 2.15 - Image of relative orientation of the TLS point clouds

There are several ways to proceed to the registration of the TLS point clouds (Bryan et al. 2009):

- Using a control survey, with total station, where at least 3 control points are common to each point cloud; the points can be materialized using targets and better results are obtained if automatic identification is performed.
- Using coded targets (spheres, chess boards, colored circles, etc.) that are automatically identified by software and then used to calculate the required transformations needed to orient the point clouds, without any control survey.
- Automatic registration of point clouds combining image processing techniques with the identification of geometric features in the point clouds.

- ❑ Using natural points of the features recorded to proceed to an initial registration followed by an optimization procedure using an algorithm such as Iterative Closest Point, usually referred as ICP (Besl & McKay 1992). In this situation, it is necessary to be careful about the points that are picked by the operator.

Leica Geosystems and Faro are the major companies owning the laser scanners and software used to process the scans. From Leica there is the Leica Cyclone software and from Faro the Scene software to orient and register the scan data. Other processing software can be JRC 3D Reconstructor (Gexcel), Riscan pro (Riegl), Z+F LaserControl (Z+F), and Trimble RealWorks (Trimble), among others.

TLS survey varies according to the number of scans, point density, resolution (measurements per scan), color, object size and complexity and environment conditions.

Measurement accuracy

A number of factors affect the accuracy of the point cloud data including instrument calibration, quality control measures, number of control points, the surface reflectivity, the angle of incidence between scanner and target, and the range to the target object (measurements further from the instrument are less accurate).

Point Density

Point density is the average distance between XYZ coordinates in a point cloud. Point density or spacing is also referred to as data resolution. To determine the appropriate point density for scanning an object one should consider the minimum feature size to detect and the accuracy of the scan system. A final consideration with regards to point density is file size and scan time. While maxing out data resolution might be tempting, doing so greatly increases data acquisition time and resulting file size (English Heritage 2009). Resolution describes the ability to detect small objects or object features in the point cloud.

The scan resolution can be as detailed as 1 point every 3 mm at a distance of 10m, this is a resolution of 3mm (at 10m). A resolution of 6mm (at 10m) means there is 1 point every 6mm at 10m distance.

One important consideration is the point spacing at which the scanning will be carried out. Laser scanning data capture must take into consideration a balance between:

- ❑ Scan density required to enable suitable identification for modelling purposes
- ❑ Site time available for data capture
- ❑ Resultant file sizes, and the ability to handle large data sets
- ❑ Potential future uses of the data by all stakeholders
- ❑ Amount of coverage required.

Survey Accuracy

Accuracy refers to the closeness of the survey measurements and point cloud to their real world position. It can be influenced by the accuracy of the survey control network, the accuracy of the instrumentation being used, or the accuracy of scans registration onto the control framework (Plowman Craven, 2017).

2.3.4. ADP and TLS comparison

TLS and ADP techniques are two non-contact surveying techniques that have been successfully applied within several fields including archaeology, civil engineering, biology, heritage sites, forensic science, and mechanical engineering. The advantage of these techniques are their speed, reliability and quality of data generated (Armesto-González et al., 2010; Mateus, 2012). These techniques also allow the object survey without contact, which avoids alteration or destruction of materials, and surveying inaccessible parts of the object without safety risks.

While the ADP methods are based on images, TLS relies on laser beams. ADP is generally a technique with lower cost, especially if done with in house users. Usually, it can be applied to smaller objects through handheld camera (or handheld camera attached to a mast) where it captures more detail, or to bigger size objects through aerial drones and balloons, capturing less detail. The laser scanning is particularly suitable to document objects with more complex geometry and it has higher costs. With recent developments in computer vision, many of the photogrammetric steps are now fully automatic (Snavely et al. 2006; Wu et al. 2011), making this technique comparable with TLS in terms of speed and accuracy. Integration of the two processes may be used: the laser scanning can be used to set the overall geometry, and photogrammetry to refine representation of the edges of objects (Mateus 2012). Software like *Visual SFM*, and *my3dscanner* create point clouds and meshes through various photos. Software like *JRC 3D Reconstructor*, *Leica Cyclone* and *MeshLab* can process and orient separate point clouds into a Point Cloud Model (PCM).

TLS point clouds usually contain highly accurate 3D data but it is also very expensive. Photogrammetry point clouds can have high or low accuracy depending on the tools and workflow one uses to create them. Parameters like the camera shooting distance, percentage of photo overlaps, number of overlapping photos, camera intersection angles, and angles of incidence interfere in the quality of the 3D reconstruction. The level of detail and accuracy of the data should be connected with the purpose, the intent of its usage.

We observe in Figure 2.16 a comparison of TLS and ADP building survey. In this comparison the overall building geometry and deformations can be satisfactorily understood using ADP. This is an important result since ADP can be more accessible to non-specialized users and cheaper than TLS. Images were taken with an iPhone 4S camera in half a day and all the processing took approximately two days (see Mateus et al (2012) for more information).

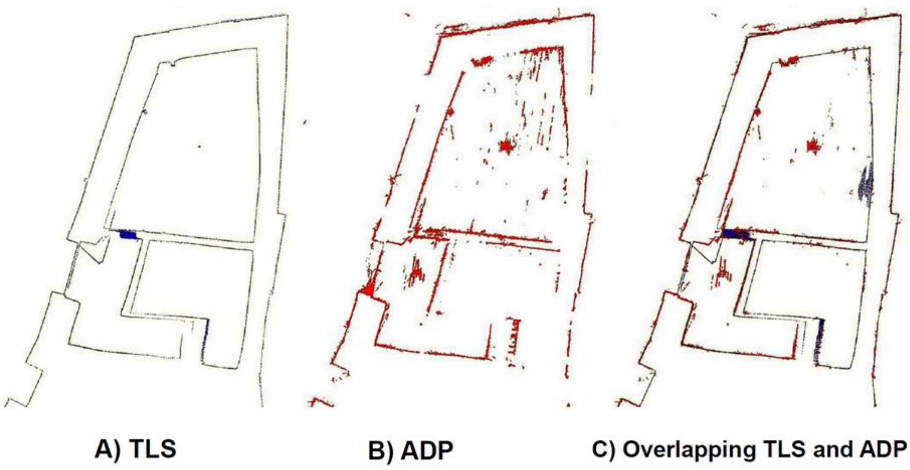


Figure 2.16 - Comparison of TLS model (left) with ADP model (center) with overlapping (right). Source: Image courtesy Mateus et al ,(2012)

In the ADP survey there was some difficulty to connect the inside and outside of building. It was observed differences up to 2 cm In the comparison between the TLS and ADP point cloud models. It is important to understand that it was being compared the output of a camera phone with a laser scanning output.

2.4. Point cloud data outputs and limitations

We are about to consider all the possible types of data (2D and 3D) and models (2D and 3D) obtained from the surveys that are usually used for the virtual building geometric construction and analyses.

By 3D or 2D data we consider what can be primarily obtained through processes of survey of the architectural object or what can derive from it as an intermediate step for generating additional data. The 2D data consists in data with a two dimensional referential axis, like for example imagery from digital cameras. The 3D data has a three dimensional referential (x,y,z) and it can be for example point clouds from TLS before being registered and oriented into a PCM. The concept of 3D or 2D data models refers to information structured up to some level, representing some building characteristics that were selected for a particular purpose of use. It is about breaking a building in parts, generating segmentation criteria and, associating information to those parts and how do they relate to each other. It is also about the criteria to define the depth of information that is necessary to gather about the different parts of the existing building when compared with the planning strategy to be developed. It can be for example a set of 2D CAD drawings, point clouds produced from images, mesh surfaces obtained by triangulation of point clouds. A simple 3D geometric model, a parametric model or a Building Information Model (BIMs).

To analyse the 2D and 3D data one chooses different software to visualize and work with building data. To be able to use the right software tools, survey data needs to be imported into them; the data needs to be readable. At least, the file format has to be compatible with the software that is going to be used. This can result in data transformations or merges of different kinds of data: a previously generated model can be used as input data to produce more elaborate models. For example point cloud models can be converted into different data formats like polygon models (mesh), NURBS models (non-uniform rational B-Splines), or CAD models (models of lines – wireframe) by a process commonly referred to as 3D surface reconstruction (Remondino, 2003).

A mesh is a spatial arrangement of polygons adjacent to each other, and although its faces can have any number of sides and be of any size, they usually are triangles. The mesh is created from a point cloud using mathematical functions of interpolation that, in conformance with stipulated criteria, allow the vertices and faces to be defined as can be observed in Figure 2.17(left). Alternative to mesh models we have the NURBS models (non-uniform rational B-Splines). This model is an assembly of surfaces generated by non-uniform rational B-splines. These lines create curves influenced by the position of controlling points as visualized in Figure 2.17 (right). NURBS are often used to transfer surface geometry between software (Hollister 2001).

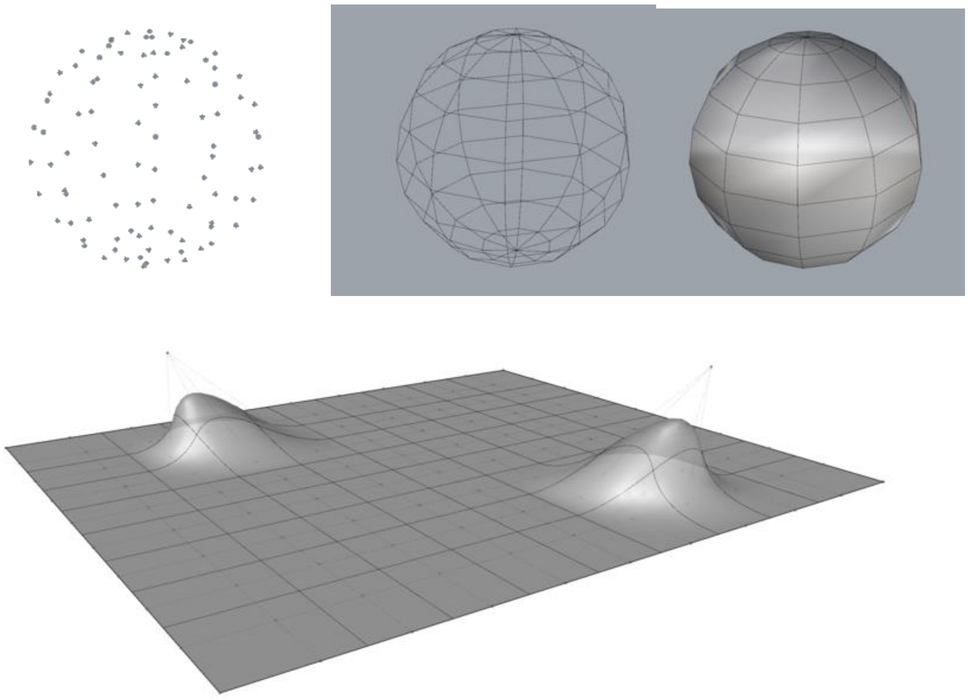


Figure 2.17- top: mesh production; bottom: NURBS surface

As described in Section 2.3.1, it is possible to obtain 3D models, like point clouds, from the 2D data, like photos. Obtaining 2D data from 3D models is also possible; point clouds can be processed and oriented into more structured data, the PCM (mentioned in Chapter 2) or the mesh models. Then these 3D models can also be transformed into NURBS models. From the structured data, one can extract images, section images and ortho-images (2D data). This process is illustrated in the diagram shown in Figure 2.18.

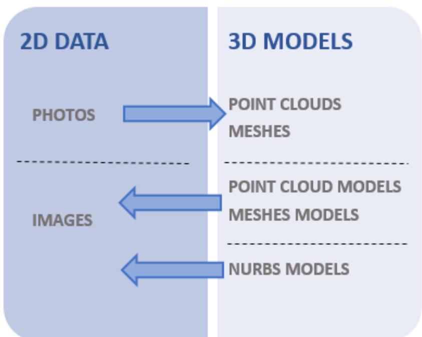


Figure 2.18 - Possible connections between 2D and 3D data.

The TLS and ADP PCM contribute for the improvement of the quality of data on which different analysis are based on. There are different kind of outputs that can be extracted from PCM, that contribute for building analysis. One can visualize PCM with different visualization options, which enhance the understanding of what the points correspond for. Ortho-images that are plans, sections and elevation of the geometry of the building can also be extracted. Besides geometric data one can extract data about the state of the building from PCM. Examples of this monitoring data can be thermal imagery, reflectance images or deformation images.

2.4.1. Point clouds outputs

PCM visualization

PCM have several options for coloring depending on the software. The PCM visualization can be color mapped intensity (maps the intensity value to a wide color range), shown in Figure 2.19.

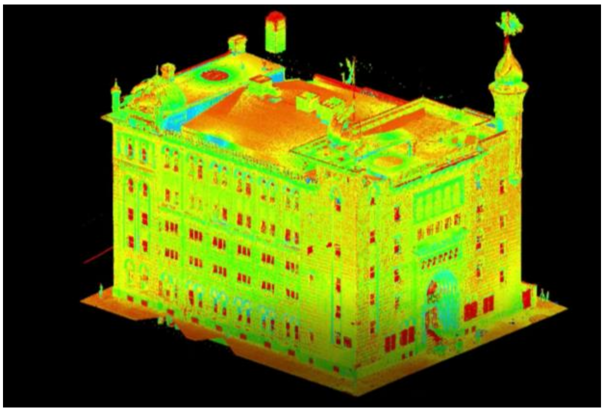


Figure 2.19-PCM with intensity color.Source: image courtesy The Beck Group

It can be visualized with grayscale intensity (maps the intensity to a grayscale value), Figure 2.20:

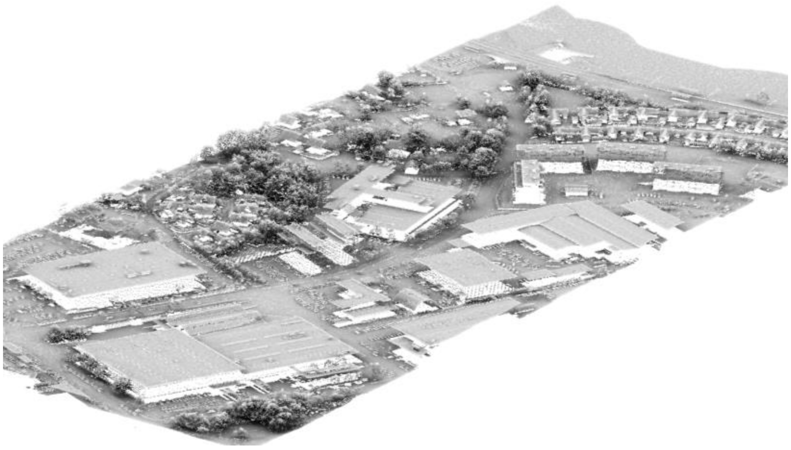


Figure 2.20- grayscale PCM

The coloration of PCM can be based on the R, G,B values(Figure 2.21);

Figure 2.21- PCM colored with with RGB values. Source: image courtesy ArcHC_3D

The PCM can have color ranges based on X, Y, or Z values (maps the dimensional value to a color range). This allows analysis of terrain variation and building heights through the analysis of z values, observed in figure 2.22.

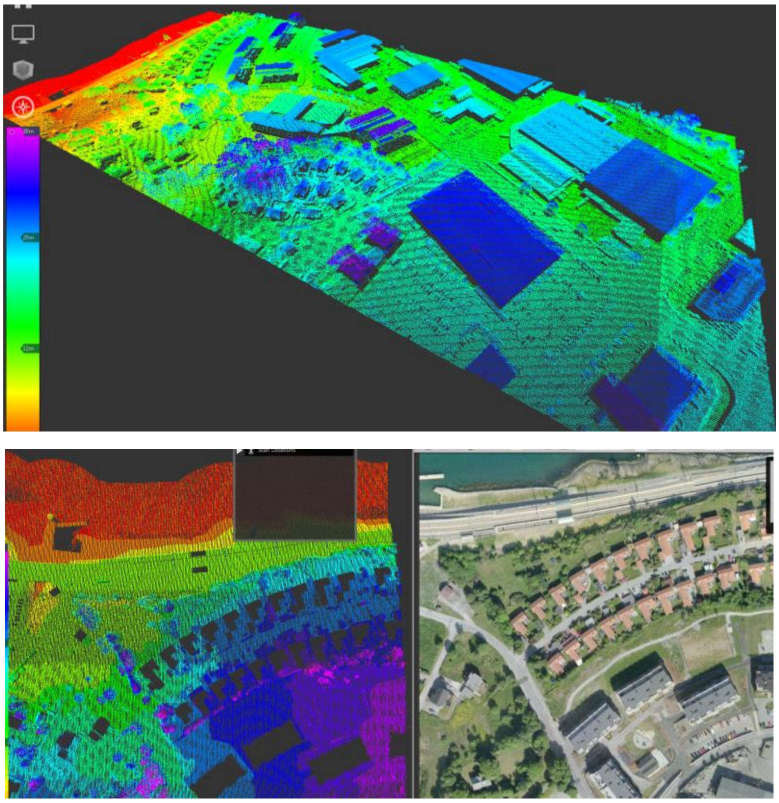


Figure 2.22 - PCM can have color ranges based on elevation values. Source: right bottom image, Google maps

The color of PCM can also be based on the color of the point normals, Figure 2.23:

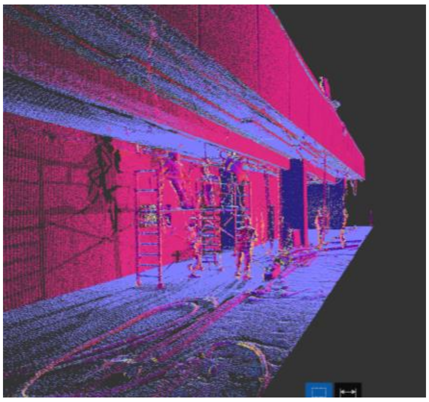


Figure 2.23- PCM colored by normals

One can also visualize the PCM color by point clouds, this is, each point cloud (corresponding to one scan) is assigned one color, like figure 2.24 exemplifies:

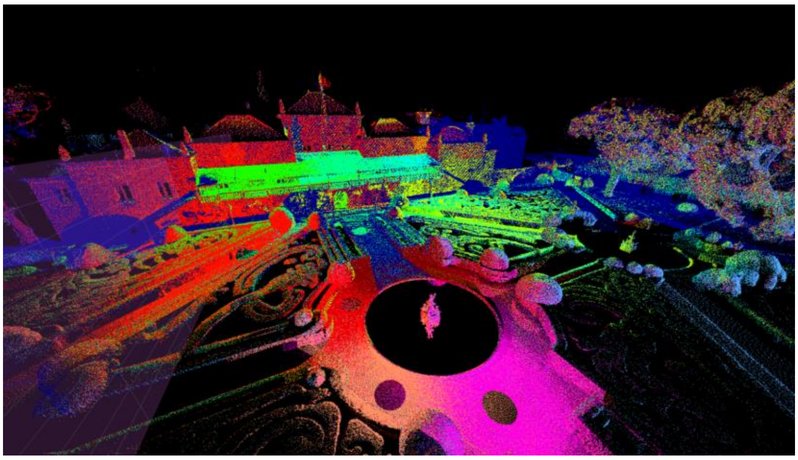


Figure 2.24- PCM colored by point clouds single colo. Source:image courtesy ArcHC_3D

Ortho-images

Ortho-images are obtained through the orthogonal projection of a plane in the 3D model with radiometric information associated (RGB values, laser scanning intensity values, among others). Ortho-images can be elevations and sections like Figure 2.25 or floorplans like Figure 2.26.

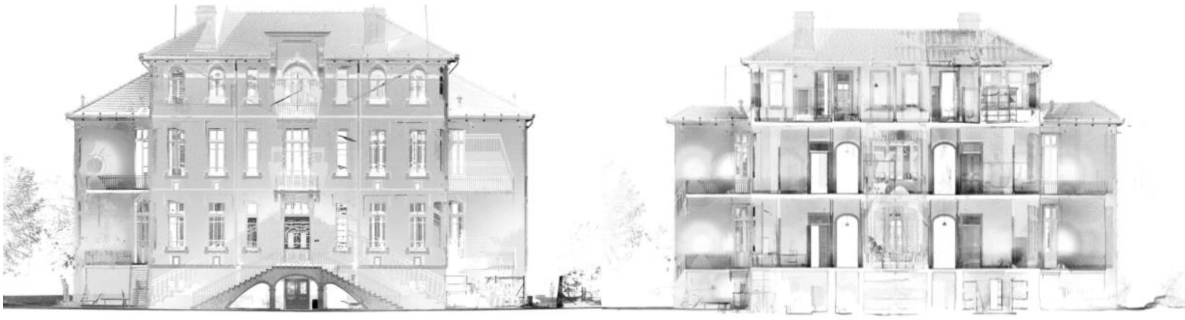


Figure 2.25 - Orthoimages - elevation on the left and section on the right

Figure 2.26 - Orthoimages - floorplan

One can also extract PCM sections, shown in Figure 2.27, and merge this section with an ortho-image.

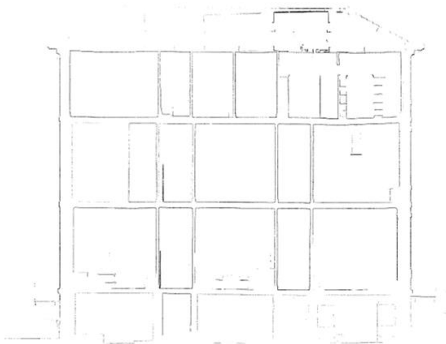


Figure 2.27- PCM section

Figure 2.28 shows the process of creating a plane with thickness, that will allow extracting a section image of the PCM. This image and the ortho-image can be merged and developed into a section illustration like the one observed in the end of Figure 2.28.

Figure 2.28- Process of obtaining a section merged with an ortho-image. Source: Image courtesy Mateus (2013)

A floor plan/ site plan ortho-image and a floor plan/ site plan section can also be merged and developed into an illustration like the one observed in Figure 2.29.

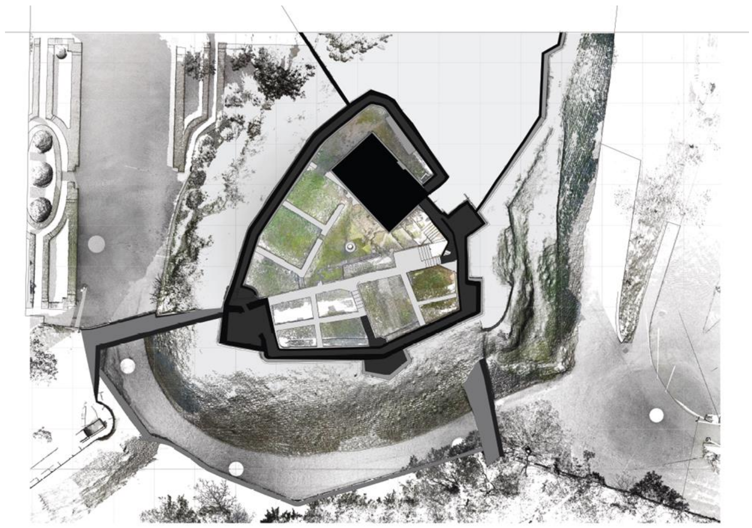


Figure 2.29- Floorplan PCM section merged with an ortho-image. Source: Image courtesy João Covas.

Reflectance images

A reflectance survey is the quantification of radiation reflected or emitted from surfaces. Each surface material has a different wavelength reflection characteristic from which one can produce spectral classifications. The spectral distributions are shown in reflectance/intensity images represented by distinct shades (Mateus 2012).

Laser scanners emit laser beams and measure the intensity of its reflection in surfaces (intensity of the returning laser beams). Reflectance images can be texturized in point clouds (Figure 2.30) generating 2D thematic maps, where we identify and characterize different kinds of materials. Each point belonging to the set of point instead of having a RGB value can have an intensity/reflectance color value. (Mateus 2012; Mateus et al. 2012; Docci 2005).

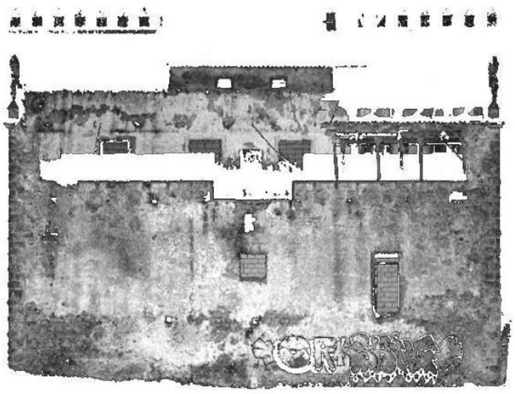


Figure 2.30- Reflectance (laser wavelenght = 683nm) image of Valflores palace. Source: Image courtesy Mateus (2012)

Thermal images

One can also integrate infrared thermal images in the point cloud models to optimize the recognition of thermal anomaly location. Infrared thermography (IRT) detects infrared energy emitted from a surface and converts it to temperature. Its product is an image of temperature distribution (Figure 2.31), identifying thermal differences on the surface of an object. The thermal images are texturized in 3D models.

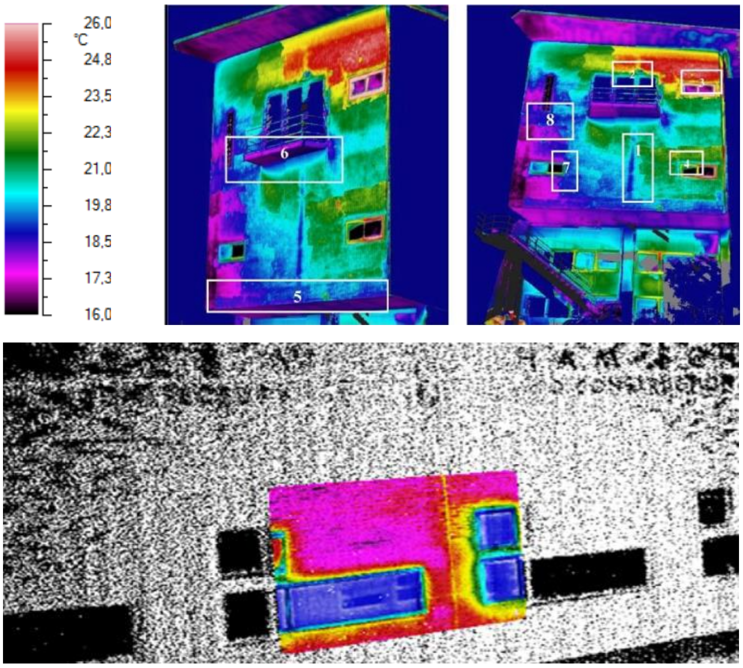


Figure 2.31 -top image: IR thermal image. Source: Image courtesy (Alba et al. 2011), with permission from CC BY 3.0 ; bottom image: IR thermal image projected in a point cloud. Source: Image courtesy (Wang et al., 2013),with permission from ASCE

2.4.2. Point clouds limitation

Point clouds document the position, size and dimensions of all visible surfaces, components and context of a building, referencing them to a local or national coordinate system. The fact that point clouds can only provide "epidermic" information is the first limitation we outline. Everything that is under the building element surface needs to be recorded with other techniques.

Point clouds are not able to study cultural, historical and architectural values, or analyse environmental, and mechanical building performances. The valuable information extracted from point clouds for the building intervention is more connected with geometry and some times usage and structural analysis, whenever this kind of information is visible.

The outputs described in Section 2.4.1, are the major data extracted from point clouds that allow to perform building analysis to understand the geometry and current state of building. The limitations of point clouds are connected with the PCM use and visualization in 3D software tools, particularly when performing the geometric analysis, the modeling from the PCM.

The size of each point cloud file, which can be bigger than 100Gb in a building survey, can be a problem for the visualization in software that is not a point cloud viewer. This will result in the software "freezing" or slower software performance. Possible solutions can be the segmentation of the point cloud in logic areas. For example each building level and the facades correspond to a different point cloud file. Complementing this workflow one can decimate the point cloud by "asking" the software to delete points. From our experience it would be relevant if one could chose the areas where software would delete more points than on other areas, instead of a random equal removal. Handling efficiently huge point clouds demands high scalability, speed and computational adaptation (cloud computing) to answer specific needs.

Another limitation is the clutter and occlusion issues. Point clouds can have unwanted data resulting from reflective elements, or temporary or moving elements like people, vegetation, car and dust. All this information is stored and not differentiated from the relevant information in a point cloud. Interpreting point clouds requires specific knowledge and analytical skills in order to extract pertinent information for the end user from the unwanted information. Extracting information from the point cloud is time-consuming, error-prone and can lead to a loss of vital information. The process of cleaning a point cloud is majorly manual.

For the analysis of point clouds, points will still just be geometric points with no intelligence associated. Programming should enable us to attach metadata to each individual point or set of points. Points would "know" where they belong in 3D space being assigned to building elements, like walls, doors,windows, etc. If each point cloud could have this sort of information, the "dumb" point cloud would be replacement by a "smart" one that one would use to index and access the data. identifying links and relations within segmented objects becomes essential to truly understand how each spatial entity relates to its surroundings redefining big point cloud data as smart data (Poux et al., 2016).

To be effective in the manipulation of point cloud data, especially within modeling software tools (where the files can be really heavy), the computer hardware I recommend are the following (or similar): i7 processor, 12-core or better, 64gb ram (the more RAM the computer has, the better is the performance with point cloud data) and dual 4-6gb graphics (gaming engine).

2.5. Conclusion

There is always the need to structure and analyse information about a building if we are going to intervene on it. This chapter outlined the use of existing information, that does not correspond to the actual state of the building, like CAD drawings, or is not enough like hand drawings and photos, to base project decisions. More accurate and up to date information can be generated through ADP and TLS. ADP converts 2D images back into 3D world, using the basic principle of triangulation, whereby intersecting lines in space are used to compute the location of a point in all three dimensions. The 3D points produced from measurements of multiple photographs are the final product of photogrammetry. TLS captures multiple point clouds, by positioning a laser scanning system at various points of view, around the structure under study.

The final product of ADP and TLS are the point clouds, which can be used together to complement each other. The combination of these techniques with traditional RTS survey provide an accurate and up to date base that, along with other existing information, allow the planning of building interventions. Point clouds document the position, size and dimensions of all visible surfaces, components and context of a building, referencing them to a local or national coordinate system. The fact that point clouds can only provide visible information is the first limitation we outline. Everything that is under the building element surface needs to be recorded with other techniques.

Point clouds are also not able to study cultural, historical and architectural values, or analyze environmental, and mechanical building performances. The valuable information extracted from point clouds for the building intervention is more connected with geometry and structural deformation analysis, whenever this information is visible. The PCM geometry analysis is where the point cloud data has more limitations, regarding its use for creating virtual models. In the next chapter it will be described how to use the point cloud data to perform building analysis.

We have seen in this chapter the need for better use of documentation in which architectural project decisions are made. We can outline three key points:

- ❑ it is important that one does not assume that existing documentation (plans, sections, elevations) gives a reliable depiction of the building as it is. The information should be checked, understanding if it is accurate and up to date, otherwise should be used as historical document, to understand building evolution, not as a base for intervention;

- ❑ Different kind of data, not just geometric, is needed as base for the analysis of the current building state. Examples can be data for material analysis and for deformation analysis, among others;
- ❑ Different kind of data should be used to complement each other: drawings, photos and PCM should be consulted at the same time. Workflows to connect them in a more integrated way should be implemented.

3

Analyzing Building Data

From the described data used for the analysis of the current building state, the present thesis will focus on the geometric and non-geometric information that refer to physical characteristics of the built fabric, such as materials, appearance and condition. It will also be referred, to some extent, the environmental and structural building performance. The cultural, historical and architectural building information will not be outlined. It is considered essential to the building understanding but it is not part of the thesis scopus. This chapter describes how to analyze data, from the point clouds and through the use of BIM tools, in order to extract and structure information relevant to the architectural intervention. First, Section 3.1 describes different analysis processes of the building state through point cloud data, while Section 3.2 uses point cloud data to analyze building element geometry. Section 3.3 focuses on Building Information Modeling (BIM) as a building information analysis tool, and it is subdivided in four subsections: Section 3.3.1 defines BIM; Section 3.3.2 describes its history and current state of art; Section 3.3.3 describes BIM tools features; and Section 3.3.4 outlines BIM as a tool to analyse data. Figure 3.1 illustrates a schematic diagram of the Chapter 3 subjects summary.

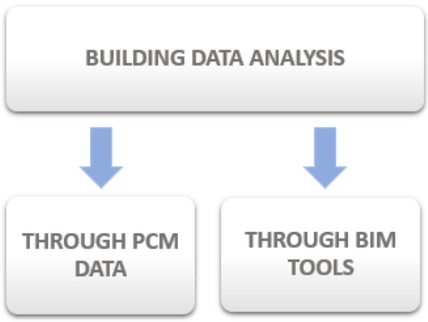


Figure 3.1- schematic diagram of the Chapter 3 subjects summary

3.1. Analysis of the building state through point cloud data

Once the data is structured (see outcomes Chapter 2), one can extract information relevant to the study of the building. There are different types of analysis including:

- ❑ the analysis of the current state of building, that includes material analysis through radiometric studies and, material temperature analysis through infrared thermography studies;
- ❑ building deformation analysis;
- ❑ geometric studies;
- ❑ historical studies;
- ❑ and building information modeling (BIM) for analysing and managing building information.

This section focuses on the analysis of point cloud data or data obtained from point clouds and how it helps structuring and informing project decisions.

3.1.1. Radiometric information analysis

Observing a radiometric image, one can find out the existence of different materials, mainly because different materials have different color representations. This difference can be justified with the existence of pathologies, like the presence of moisture, allowing to diagnose building damages (Armesto-González et al. 2010). Texturizing the radiometric/reflectance images into PCM refines the visual analysis allowing to better and faster understand how the intensity colors relate between building elements. This method permits analysis of the state of building material and possible damage prevention.

González-Jorge et al. (2012) described a method to identify the presence of water through reflectance images. Water is usually associated with the appearance of efflorescence and vegetation and it contributes to deterioration of materials like concrete (observe first image of Figure 3.2), stone and wood, among others, leading to superficial and structural damages. In order to identify the source of the damage, one can analyze reflectance images observing the different shades and connecting them to different materials. This helps locating the biological presence, as we confirm in Figure 3.2, and analogously identifying the presence of water.

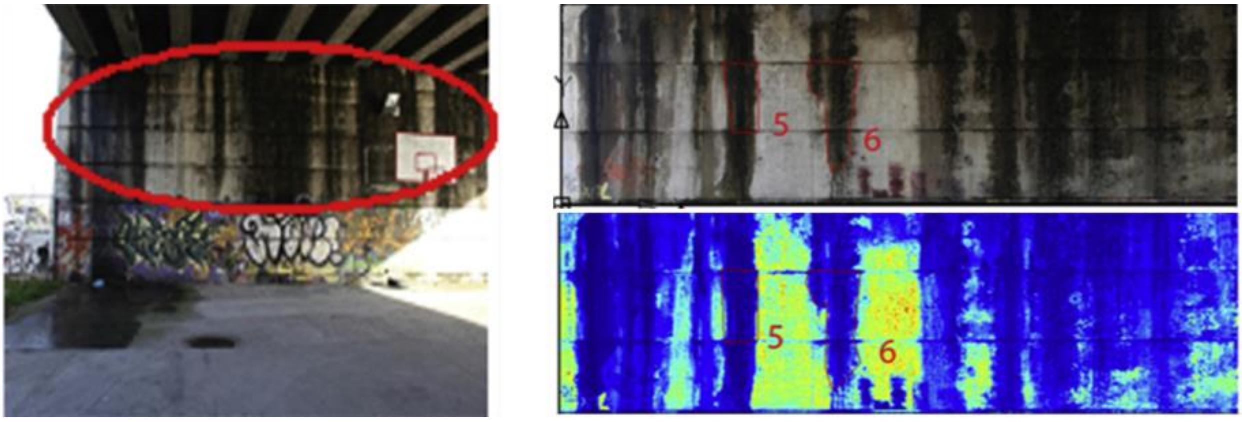


Figure 3.2 - Presence of biological activity in a concrete wall. Source:image courtesy González-Jorge et al. (2012)[11], with permission from Elsevier

According to Mateus et al. (2012), another way of identifying biological presence is to combine infrared (IR) laser information with red laser information. This combined information allows the calculation of the normalized difference vegetation index (NDVI), which is a way of detecting chlorophyll presence in the surfaces (Figure 3.3).

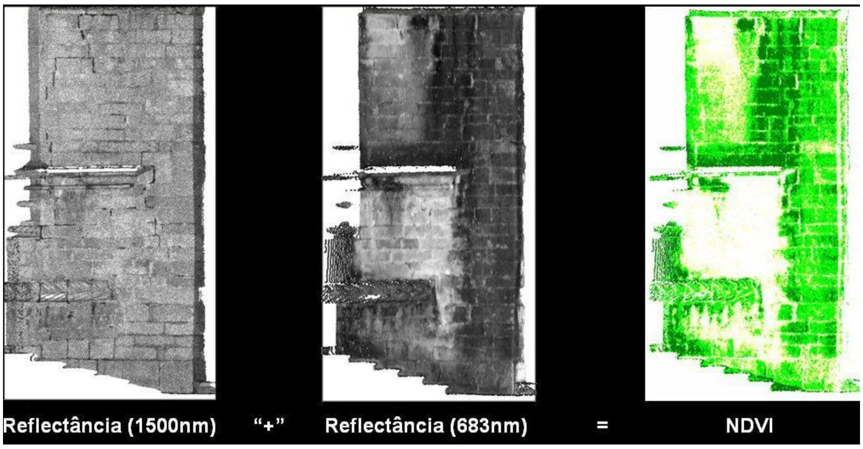


Figure 3.3- Chlorophyll identification through different spectral laser combination. Source: Image courtesy Mateus (2012)

Radiometric information not only confirms the presence of material damages but it also monitors its evolution. Amaral et al. (2013) presented a study where it was possible to obtain wall cracks width, depth and length through point cloud analysis (from laser survey). These allow evaluating the degrading evolution state of a crack. The position and condition of the crack, provided by point clouds, contribute to the diagnosis and recovery intervention of the wall.

[11] Reprinted from Construction and Building Materials , Volume 31, "Monitoring biological crusts in civil engineering structures using intensity data from terrestrial laser scanners",González-Jorge H., Gonzalez-Aguilera D., Rodriguez-Gonzalvez P. , Arias P, Copyright (2012), with permission from Elsevier

Another approach of the use of radiometric surveys is described in Rizzi et al. (2007), where it is observed that one can analyze non-visible material skins situated under the visible material layer of a painting through IR lasers. The first layers of a painting are partially transparent to IR radiation permitting the discovery of ancient paintings under the visible ones, illustrated in Figure 3.4.

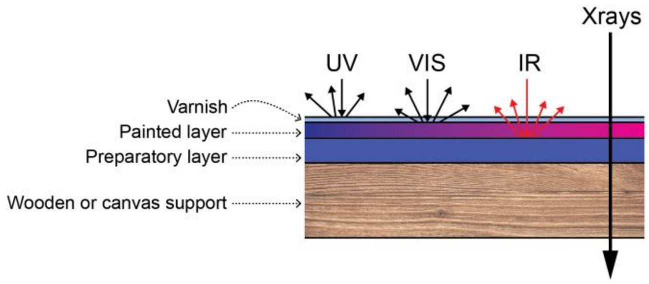


Figure 3.4- Wavebands that can be used to investigate layers of a painting. Image based in Rizzi et al. (2007)

3.1.2. Deformation analysis information extraction

One can obtain deformation images from point clouds by placing reference planes and measuring the distance from them to the point cloud points. These distances are represented in depth maps and are texturized in the point cloud model, allowing the analysis of material deformation levels. An example of such a study is available in Figure 3.5, taken from a study done in ArcHC_3D survey project, Palace of Valflores. Figure 3.5 shows the distance between a plane placed in the connection of the wall, represented in blue and considered 0 cm offset from the plane, and the most distant point of the wall, represented in red and considered averagely 10 cm offset from the plane. The wall is more deformed in the middle, where one can assume a perpendicular wall to be missing, that would pull the one in study and prevent deformation for example.

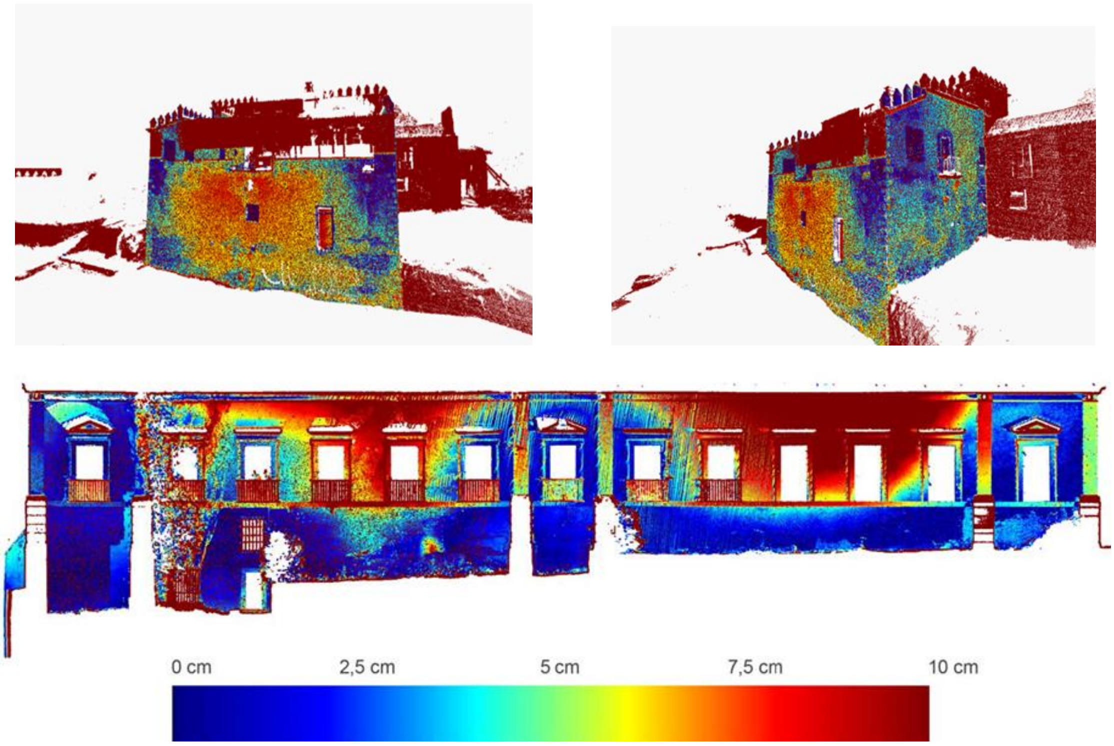


Figure 3.5 - Deformation analysis of a wall. Source: Image courtesy Mateus (2013)

Through deformation analyses, we can also measure the bowing of wall cladding panels and identify wall surface delamination locations (Mateus et al. 2012; Al-Neshawy et al. 2009) (Figure 3.6).

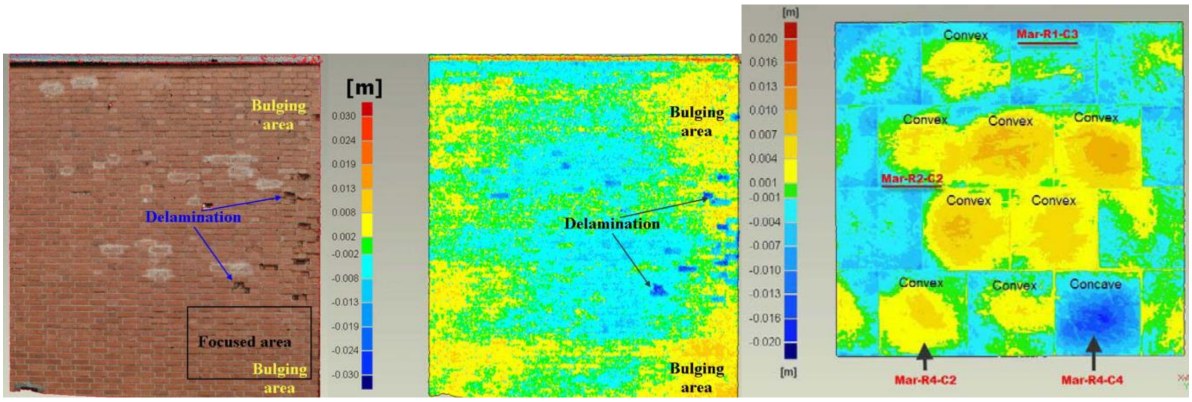


Figure 3.6 - Left: Bricks delamination analyses from TLS data; right: deformation of wall cladding panels analyses through TLS Source: Image courtesy Al-Neshawy et al.(2009) published under CC BY-SA 4.0 licence.

3.1.3. Analysis of infrared thermography information texturized into PCM

Thermal images projected into point cloud models optimize the recognition and comprehension of anomalies and their correlations with other building elements. The surface temperature results from heat flow and boundary conditions, giving information about the object state. Heat passes rapidly through the most cohesive materials and the materials with higher thermal effusivity (Alba et al. 2011). Therefore, IR thermography cameras allow non-contact monitoring of the building structure, identifying its defects and thermal irregularities. Figure 3.7 shows a PCM with thermal image projected point colors where a flow of higher temperatures is observed, allowing to identify where the wall needs to be consolidated.

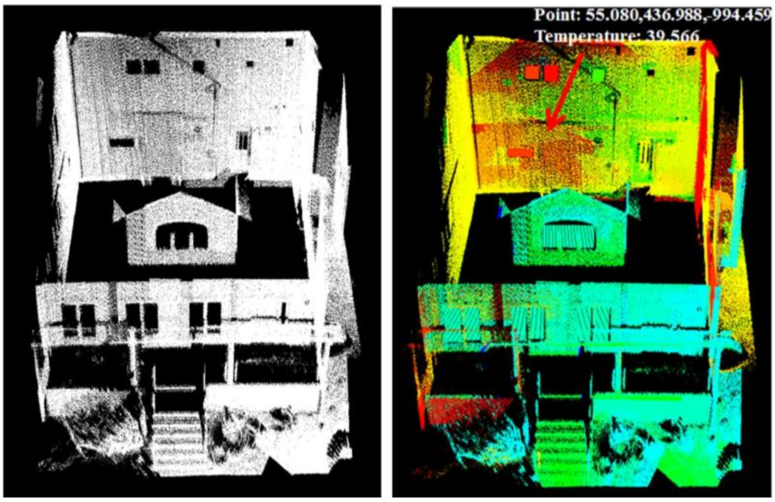


Figure 3.7- 3D point cloud without color; 3D thermal point cloud colored by normalized temperature values. Source: Image courtesy (Wang et al., 2013), with permission from ASCE

3.2. Analysis of building elements geometry based on point cloud data

When a project is starting, the first step will be to study the building geometry. Anyone in the project needs to understand how elements relate to each other, what dimensions and scale are present, and how spaces connect. The understanding of elements position and consequential space dimensions is in itself a study of the building, allowing to plan possible future usages. In this Section, we are not focusing on the deformation or state of elements but on the dimensions, shape and position of individual elements that compose the building. The study of geometry can be realized by generating 3D models or CAD drawings through tracing over images like vertical or horizontal PCM sections and ortho-images, shown in Figure 3.8.

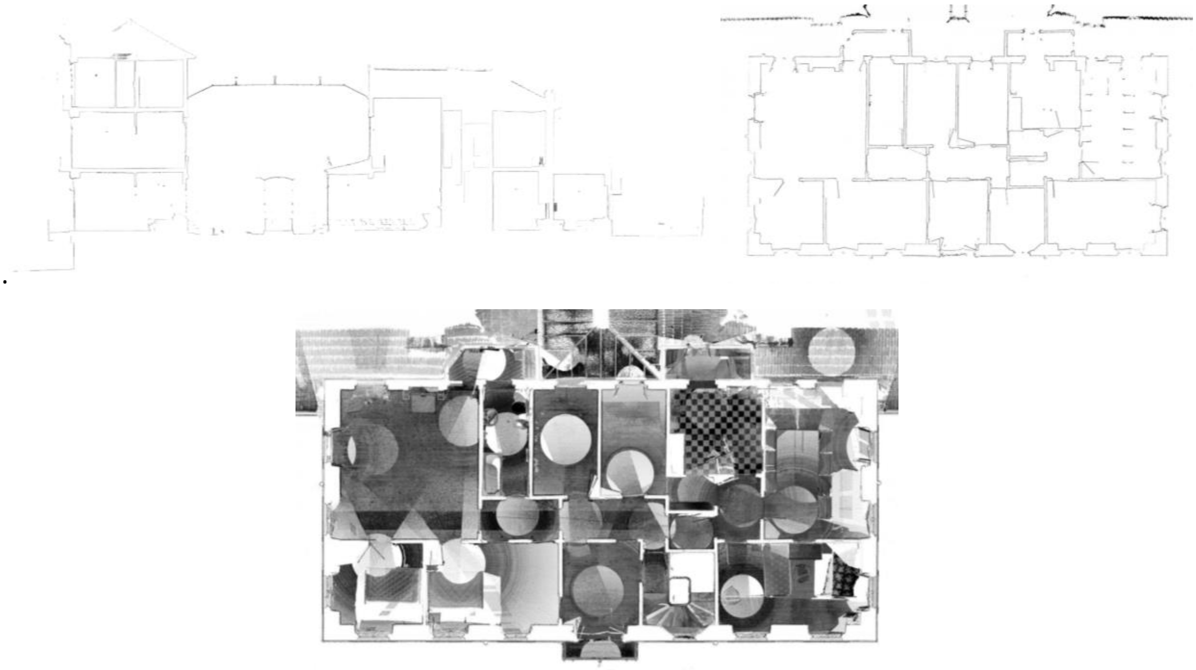


Figure 3.8 - Top images: vertical and horizontal sections; bottom image: floorplan ortho-images. Source: image courtesy ArcHC_3D

Figure 3.9 shows on the left an ortho-image used to trace a 2D CAD drawing elevation, that is observed on the right image below. This can be done through software like AutoCAD®.

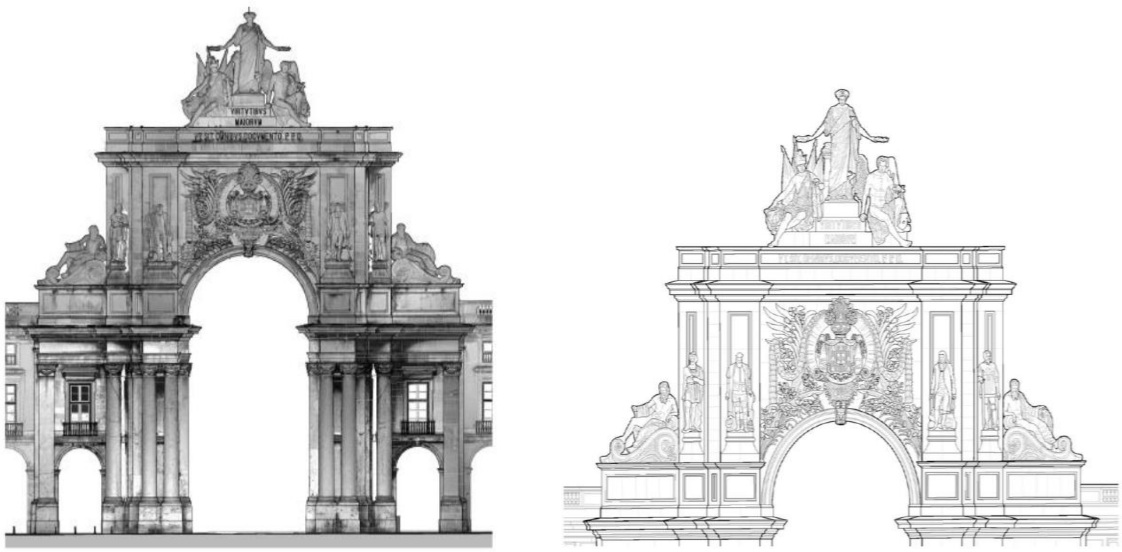


Figure 3.9- 2D CAD manually traced over ortho-image. Source: Image courtesy Mateus (2012).

One can build 3D models by manually tracing over imagery (mostly ortho-images), 2D CAD data (obtained from the images) and sections obtained from the PCM (Figure 3.8, top images). The resulting 3D models can be geometric models, parametric models or BIMs. The geometric model is a 3D surface model that has the position and dimensions incorporated, the parametric model also has parameters of the object in study included. Any CAD and BIM software like *AutoCAD®, ArchiCad* and *Autodesk®*

Revit® can import an image or other kind of 2D data that serves as base to the 3D model. From 3D models, we can produce renders, ortho-images, section images, among others.

Generating the model by tracing over base data is a workflow often used in the industry. Figure 3.10 shows a 3D element generated by tracing over and using profiles of CAD drawings.

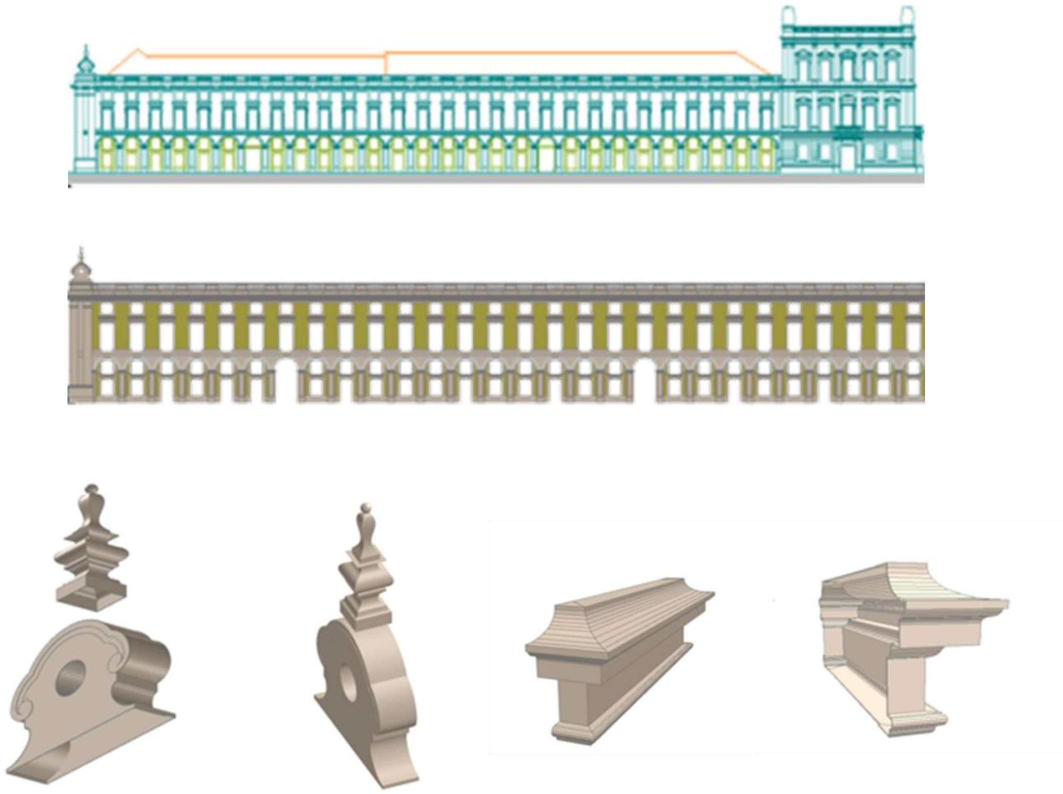


Figure 3.10 - 3D elements generated from CAD drawings in Barbosa (2011)

The workflows to obtain a 3D model from 3D data are transversal to multiple fields including mechanical engineering, aeronautics and marine industry. Chader (2008) refers to these workflows as reverse engineering workflows, as they aim at the reconstruction of geometry as it might originally have been devised. It will be described three major workflows. The first described workflow consist in creating shape bases, briefly used and then discarded, in a parametric CAD model to manually build the 3D (Chader 2008). This workflow (Figure 3.11) includes the following steps:

1. import a PCM,
2. extract cross-sections (NURBS curves) by slicing the cloud with various planes where curvatures of the points on the plane are approximated by a network of Bezier curves.
3. These curves or NURBS surfaces are imported as base into a CAD software application.

4. A 3D object is then manually drawn from the imported curves, thus leaving a number of 3D modelling choices to the engineer or designer.

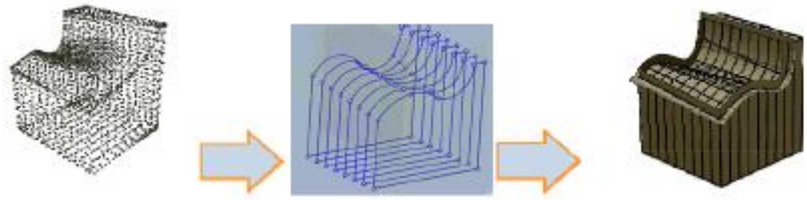


Figure 3.11– First known workflow. Source: Image courtesy Chader (2008), with permission BY-NC.

The second described workflow (Figure 3.12) includes the following steps:

1. Import a PC,
2. form a polygonal mesh,
3. and convert it to a NURBS surface patch (due to its heavy size).

The curved patches (small areas defined on the image) on the side of the NURBS are done automatically or by hand and imported as base to build a parametric model (Chader 2008).

Figure 3.12 - Second known workflow. Source: Image courtesy Chader (2008), with permission BY-NC.

The next workflows were based on software that associates scan data with the native parametric CAD commands (Chader 2008). The point cloud is imported in the CAD platform and is directly used to draw the 3D elements of the parametric model. The reverse engineering software examples, with semi-automated tools for geometry recognition in PCMs, can be Geomagic[12], Rapidform Xor[13] and 3DReshaper[14]. The "reverse engineering" workflows are pointing towards a new path, the semi-automated one, for the 3D architectural modeling.

[12] http://www.geomagic.com/en/

[13] http://www.directdimensions.com/port_featuredprojects.php?fileName=fp_rapidform

[14] http://www.3dreshaper.com/en/

The semi-automatic shape recognition in architectural modeling processes are based on the last workflow described above, where there is a CAD software tool that recognizes the shape (of the PCM or NURBS model) and semi-automatically transforms the 3D data into 3D models. There are some architectural software applications, like *Scan to Bim*[15], *Faro Point Sense* [16] *Kubit, Point Cloud Feature* extraction [17] (plugins) and *Edgewise building modeling* [18], that have an automated recognition and placement of elements, like walls, columns, pipes.

3.3. Building Information Modeling (BIM) as a tool for analysing data

A third possible way to analyse a building structure, is through the usage of Building Information Modelling (BIM) techniques. To understand how BIM can be used in an analysis process, we first need to define what BIM is in the scope of this thesis. The next sections will firstly consider the current definitions of BIM, as well as its history and context, followed by a current status review of BIM and finally looking on how to use it for analysis.

3.3.1. BIM definition

There are many definitions for the term Building Information Modeling (BIM). Kymmell (2008) defines BIM as a simulation process of the construction project in a virtual environment creating a prototype of the building. It consists of 3D models of the project components with links to all the required information connected with the project planning and construction. The National Institute of Building Standards (NIBS) describes BIM as a digital representation of physical and functional characteristics of a facility, resulting in a facility shared knowledge resource used as a reliable basis for intervention decisions during its life-cycle (NIBS 2007). The Associated General Contractors of America (AGC) emphasize the ability to virtually (re)construct structures by simulating its construction in a virtual BIMs (AGC 2008). The General Services Administration (2007) defines BIM as the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a facility. It is a data-rich, object-based, intelligent and parametric digital representation of the facility. Smith & Tardif (2009) finally distinguish the term building information model and building information modeling. They consider that any form of

[15] https://www.imaginit.com/software/imaginit-utilities-other-products/scan-to-bim
[16] http://www.faro.com/products/construction-bim-cim/faro-pointsense/
[17] https://apps.autodesk.com/ACD/pt/Detail/Index?id=8803117352142221591&appLang=en&os=Win32_64
[18] http://www.clearedge3d.com/products/edgewise/

information compilation about a building is a 'building information model' and any simulation of any real activity associated with the building process is 'building information modeling'. Building information modeling is a system approach to the building lifecycle phases based in a compilation of reliable data (building information model).

These definitions are related and complement each other. BIM is outlined as a process that uses different kinds of software which allow one to interpret and digitally record physical and functional characteristics of the as-built environment. The information is shared and used by all parties as a reliable basis for planning and simulating the intervention project. In this thesis, BIM is considered to be the process of managing structured information related to buildings. This also means that every tool involved in this process is part of BIM. Not only the typical AEC software like Autodesk® *Autodesk® Revit®* and *Archicad*, but also tools like *Autodesk® Recap®, Cloud Compare, Meshlab, Excel*, *Solibri Model Checker*, *Dynamo, Rhinoceros, Grasshopper*, among others. Note that this definition is not used or accepted in several companies in AEC industry where BIM is strongly associated with *Autodesk® Revit®* or *Archicad* 3D models.

3.3.2. BIM history and current state of the art

BIM history

From the early 1980s onwards, architects have turned to the usage of BIM, and more particularly of Computer Aided Design (CAD) tools. Soon, a large percentage of documents relating to the design and construction of buildings were made with computers. 2D CAD drawings, such as plans, sections and elevations, consist of lines and shapes, without any indication on what those lines and shapes represent, except from the drawing guidelines. CAD software can produce elements like windows with geometric precision, but does not describe its energy efficiency, cost or installation.

Slowly, the technology has continued to evolve, until another line of CAD called "object-oriented CAD" emerged in the early 1990s (Autodesk 2002). The term "object-oriented" is derived from a computer programming technique in which blocks of code are assembled like lego pieces into larger components. The elements of a building are represented as objects that contain the physical geometry, as well as many other attributes such as shape, behavior, performance data, cost, maintenance, supply and installation. These objects are called parametric objects. Parametric information is editable information in a parametric object, consisting of geometric definitions, rules and associated data

(Eastman et al. 2011). Parametric objects shall meet the membership rules so that when an object is changed, the object and its associated information are modified as well.

Three-dimensional virtual models can be divided into surface models and solid models (Smith & Tardif 2009). The components of a surface model only include information such as size, shape, location of the object in relation to other model objects (Smith & Tardif 2009). Models which contain more information than the surface models are often referred to as smart models. Solid models with parametric components are also called "object-oriented models" (Smith & Tardif 2009). The parametric information refers to information that distinguishes a particular component from other similar components. These characteristics can be programmed in the constituents of the object model, creating a smart model (Kymmell 2008). These "smart objects" are what distinguishes the geometry created by a building information modeling (BIM) from a "normal" 3D model (Smith & Tardif 2009) .

The exact start of the term "BIM" is questionable. The term came into popular use around the publication of Jerry Laiserin’s Laiserin Letter No. 15, according to Smith & Tardif (2009). According to Eastman (2011, p.354), the first documented example for the BIM concept as we know it today was a working software prototype "Building Description System". It was also documented in the journal "Automation in Construction" published by GA F. van Nederveen and Tolman December 1992 (Eastman et al. 2011).

BIM current state of the art

BIM is characterized by the availability and connectivity of all the information that became part of a construction project, such as its dimensionality, 2D, 3D, 4D (time-related), 5D (cost-related), and any other information. In such a centralized model, all information can be linked to the model and accessed (Smith & Tardif 2009). The amount of information and level of development (LOD) required will depend on the purpose. When considering the LOD of a model, one has to think about what is wanted to be to analyzed and communicated through the use of BIM (Eastman et al. 2011). The aim of the BIMs should be to explain the project, this means BIM components (3D models and information of the project) will be continuously transformed and complemented throughout the development phases of the project. This observation reinforces the importance of the process, instead of the model itself, and its dynamic character (Kymmell 2008).

BIM as a process allows the production, storage, exchange and sharing of information in a reusable manner throughout the lifecycle of a building form, constituting a concept of information management of construction projects, allowing a wide range of possibilities within the 3D approach.

BIM does not mean that all the information, from different areas, about a building should be compiled into a single file, residing on a single physical location, or maintained by a single corporate entity over the life cycle of a building (Eastman et al. 2011). The BIM implementation strategy of using a single building information model is out of reach, it would require very advanced technology and investment. No software applications or technology platforms are able to contain all the information created throughout the lifecycle of a building and make it accessible to all interested parties at the time they need it. More importantly, none is being developed. The trend in the development of software is the generation of several "Building Information Models" created by highly specialized software tools that are designed to work together. A single software that includes several specialties would increase cost and interface complexity; which would erode any functional efficiency of a single model. The complexity, cost, and functional inefficiency increases exponentially as other disciplines are added to the software (Smith & Tardif 2009). Besides, to the date, no one needed all the information about a building at once. Construction professionals can conduct a more rigorous analysis of their conceptions to minimize or reduce errors and omissions, while homeowners and builders - they have the same access in conflict detection ("clash detection") and other tools validation - will be held responsible for error detection and omissions before they result in financial losses. This is one way in which technology can help alter the current adverse weather industry to a more collaborative, simply to improve the quality of " building information" available (Smith & Tardif 2009).

The implementation of the "building information" is relatively new technology in the AEC industry, and as such, the interoperability of BIM based software still has to be fully established. Consequently, the potential of BIM in the propagation of an integrated approach and data integrity during the delivery of the project is difficult to achieve. Organizations like the International Alliance for Interoperability (IAI), the National Institute of Building Sciences (NIBS), and FIATECH are searching the area of interoperability within the AEC industry to try to establish norms and standards format that is useful and accessible (National BIM Standard Project Commission, 2007). The only uniform format and file for international interoperability between software is the Industry Foundation Classes (IFC) developed by buildingSMART International (Smith and Tardif 2009; Villafana 2011). This means that, to be compatible with models created by other software tools, it is necessary that all of them are translatable in a uniform format file, so that all object information can be transferred correctly. This is outside of any global interoperability and compliance is usually dictated by market requirements (Kymmell 2008).

Marketing strategies lead to complement each other in software, with different sets of features. Examples of major BIM platforms are *Autodesk® Revit®, Bentley Architecture, ArchiCAD, VectorWorks, Tekla Structures, the DProfiler* and *Digital Project,* among others.

Greater efficiency and productivity of the entire lifecycle of any building is one of the main reasons for the deployment of new technologies. We need to develop more efficient, less costly, faster methods to design, build, manage, operate, maintain, and reuse demolish buildings (Eastman et al . 2011) . The main features of BIM are:

- ❑ to establish and operate databases to enable collaboration;
- ❑ manage changes in project, and a change will change all related data;
- ❑ Capture and preserve information for reuse in other industry segments.

The main benefits of BIM are viewing the project through the simulation of the construction process, the collaboration that allows "Clash detection" and consequent elimination of discrepancies in the drawings thus reducing conflicts, waste and risks. It thus contributes to a process of higher quality, greater speed and productivity in the life cycle of a building (Eastman et al 2011; . Cerovsek 2011). The use of BIM tools is becoming increasingly common in the fields of architecture, design, engineering and construction. BIM passed the line between concept and research viable business tool in the first five years of this decade and is on track to become indispensable for the design and construction of buildings. BIM faces numerous obstacles to progress, such as technical barriers, legal and liability issues, regulations, inadequate business models, resistance to change, and the need to educate large numbers of professionals (Eastman, 2011).

In literature, research of BIM applications for new buildings is emerging and controls reviews, while BIM for existing structures is almost absent. Most of them were published after 2008 and increased in the latest years. Publications on information, functional, and organizational issues in the areas of maintenance and deconstruction[19] are approached distinctly and for new buildings. The merging of some of these issues is sporadic and publications dedicated to BIM for existing buildings, particularly without a pre-existing BIM model, are scarce. One of the main relevant sources is delivered by Volk et al. (2014).

BIM functionalities for new buildings initially concentrate on design and visualization, procurement, manufacturing, construction management and coordination, but, recently, research starts focusing on

[19] Deconstruction encompasses demolition and maintenance also refers to retrofit and refurbishment.

integrated project delivery (IPD) in a collaborative atmosphere considering as-built BIM information for FM, retrofit, refurbishment, renovation and deconstruction processes. There are multiple potential BIM functionalities and benefits for existing buildings, mainly for facility management (FM) or renovation, like project alternatives calculation, digital cost estimation, quantity takeoff, data management, as-built documentation, reporting tools, and quality assessment.

3.3.3. BIM tools

This Section focus on BIM tools, characteristics and goals rather than naming software and comparing it. Software keeps evolving, what is used today will be outdated sometimes in months. What is considered important in this thesis is not the tools themselves, but how they function. Autodesk® Revit® and Archicad are progressively substituting *AutoCAD®*, they may never replace it for some tasks but they might reduce to a plugin use. The future is unknown but it is probable that a better tool will replace the ones we know today or that known tools all become part of a bigger platform that incorporates all. So, although we refer to software names, since they are the tools we actually use nowadays, it is the software application core values that are going to be addressed in this section.

The BIM core features which are fundamental requirements for any software to become BIM compliant are: modeling parametric objects, bi-directional associativity components, intelligent modelling, interoperability capabilities and collaboration (Bilal et al. ,2015).

Parametric model

A parametric model is a 3D model formed by objects with behaviours and attributes of real-world materials, assemblies, and equipment, that have geometric and non-geometric data, constrained by parameters and rules.

Bi-directional Associativity

Model elements, views, and annotations are an essential part of BIMs. Changing one of them will probably modify other components, for example when we change a wall it will move associated walls and changing its view in all views. This is the bi-directional associativity and it complements parametric modelling by showing the impact of design changes and propagating them automatically to the relevant parts of the building model in real-time (Bilal et al. 2015)

Intelligent modelling

The ability to attach non geometric data with building objects and extract it repeatedly for different analytical and reporting purposes is called intelligent modelling.This non geometric data includes dimensions, quantities, relative locations, schedules, or specifications that are required for different analytical and evaluation purposes.Technically, geometries or properties are used to link data to building objects which enhances semantic capabilities of building objects, making objects richer containers of information.

Interoperability

Projects involve multiple people, which often use different applications to execute different tasks. Exchanging data among these applications is a requirement for a successful project delivery. Interoperability is the ability of software application to exchange data with different software applications. Coordination and collaboration are essential for successful project delivery, being dependent in the interoperability of the underlying software. Open data exchange standards, which are vendor-neutral data exchange file formats and have industry-wide acceptance like IFC and gbXML (Table 3.1) allow BIM software products to achieve interoperability (Bilal et al. 2015).

	Autodesk® Revit®	**MicroStation**	**ArchiCAD**	**Vectorworks**	**Digital Project**
File Extension	.rvt	.dgn	.pln	.vmx	.CATProduct
Open Standards					
Architectural Model	IFC, RVT, DWG, DGN, PLN, NWD	IFC, DGN, DWG	IFC, DWG, DGN	IFC	IFC, DWG
CAD Data	DXF, DWG	DWG, DXF	DWG, DXF	DWG, DXF	DWG, DXF
Visualisation Model	FBX, SKP, NWD	SKP, Rhino	MOV, SKP, WMF	SKP	
COBie Data	IFC, XLSX	IFC	IFC	IFC	

Table 3.1- BIM software tools and data exchange file formats

Another way of exchanging information between different software tools can be through a cloud-based platform for data exchange and collaboration between design tools like Flux.io[20]. This platform exchanges data between software, like Autodesk® Revit® [21]/Dynamo[22], Rhino[23]/Grasshopper,[24], and Excel[25], in real-time. Figure 3.13 shows a model created in Rhino, where the complex out skin geometry was developed with non parametric elements. Having the base geometry in Rhinoceros (A), this file is imported into Flux.io web platform (B) and the information is then pulled into Autodesk® Revit®, where the elements representing the shape were parametric. The BIMs was developed from this base through the combination of Autodesk® Revit® (D) and Dynamo (C) tools.

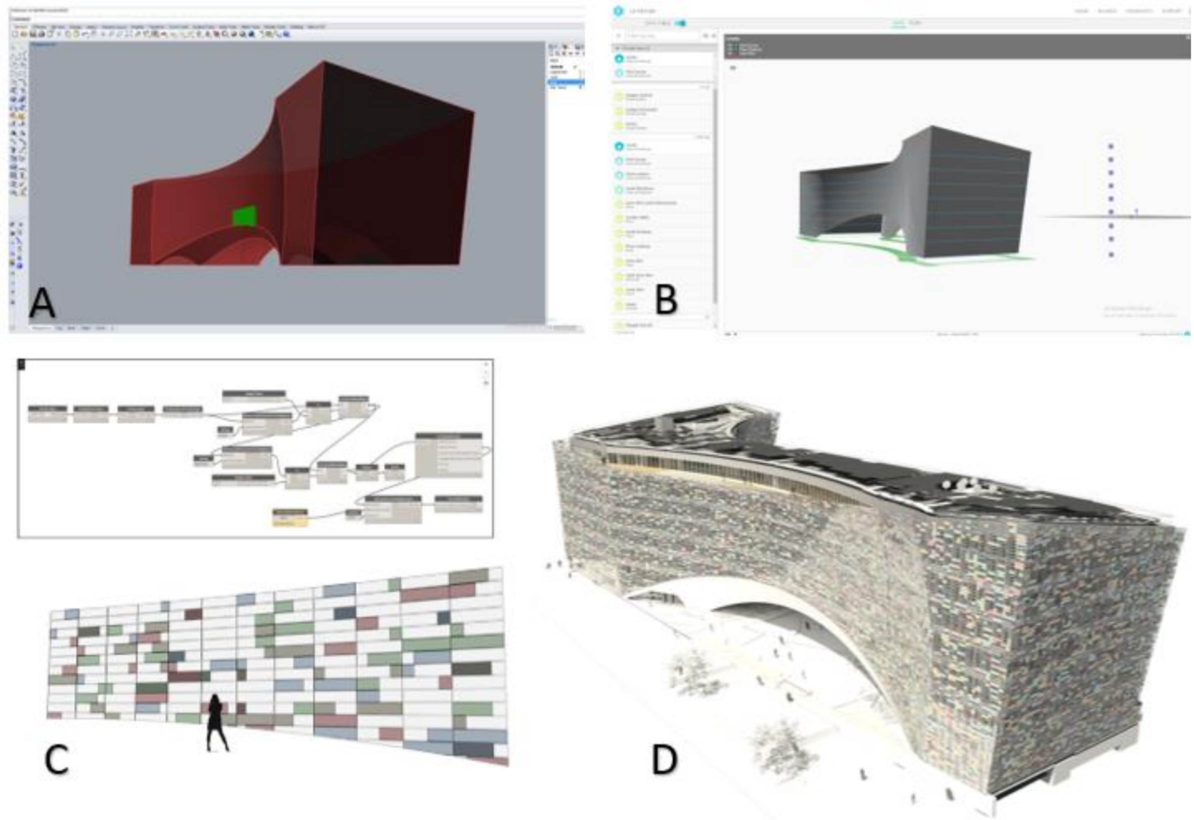


Figure 3.13- Flux.io for collaboration and real-time feedback loop between architects and engineers. Source: Image courtesy Håvard Vasshaug,from Snøhetta, presented in RTC2016

[20] https://flux.io/
[21] https://www.autodesk.com/education/free-software/Autodesk® Revit®
[22] http://dynamobim.org/
[23] https://www.rhino3d.com/
[24] http://www.grasshopper3d.com/
[25] https://products.office.com/en-us/excel

This workflow allows to create complex geometry, which is not the strong point of Autodesk® Revit®, and still use to manage information through parametric elements[26]. The interoperability and collaboration is done in real-time between architects and engineers.

Collaboration

This information is stored into a centralised database to aid information sharing and collaboration among stakeholders. The centralised database supports concurrent operations on a single building model while maintaining the model's consistency. In addition, Autodesk® Revit® supports a wide range of building performance simulations, which include energy analysis, environment impact analysis, site planning and analysis, quantity takeoff and cost estimation, construction planning and monitoring, etc. All these have encouraged the wide adoption of Autodesk® Revit® in the construction industry.

BIM core features, described above, can be a feature of a software tool or resulting from the interaction of different kind of software tools tools. Examples of software tools can be: *Autodesk® Revit®; Bentley MicroStation; Graphisoft ArchiCAD; Allplan; Bentley AECOsim; Vectorworks; Tekla Structures; Autodesk Civil 3D; Digital Project; Rhinoceros; Dynamo* plug-in for *Autodesk® Revit®; Grasshopper plug-in for Rhinoceros,* and others.

Bryde et al. (2012) discusses BIM benefits through the analysis of 35 construction projects that utilised BIM. The research concludes that BIM is an effective tool in improving data delivery. Cost, time, communication, coordination improvement and quality were positively influenced by BIM tools use. The challenges of BIM implementation are related to the change associated with the adoption of BIM and could be addressed with better training for all employees/ stakeholders involved, for example. It is still challenging that people agree in common IT platforms, cooperate and share information with each other. Another challenge can be related to extra modelling time or converting drawings into a model.

In terms of initial cost although it can be more challenging for small companies it is becoming more and more affordable. The price of most used BIM software packages is similar to the common CAD software and some vendors are selling packages that include both BIM and CAD platforms for the price of what used to be a CAD-only package. This means that the initial costs are still substantial, especially for smaller firms.

[26] For more information read: https://vasshaug.net/2015/11/30/impossible/

3.3.4. Building Information Model as a tool to analyze data

We consider BIM as a process of structuring and analysis of information. BIM allows to understand geometry and to structure information while the elements are being created. One virtually generates the object in study and to do so it is necessary a profound knowledge of it. Following the 3D model generation, there are multiple analysis one can do. These include quantities and cost estimation analysis, clash detections and coordination between several models with different data (for example checking the architectural model with the structural model form engineers), energy analysis, wind and sun analysis and, deformation analysis, among others.

BIM analysis are important in the different stages of the building construction. They can help in the initial designing phase of the buildings, allowing to understand the best orientation and volume. It can contribute for the building development efficiency through area studies, energy analysis and also it can improve the construction and building maintenance through state of building analysis, and estimating future cost of interventions, for example by obtaining a wall area that needs paint and associating it with cost of the paint.

One may need to use different models and different tools for different types of analysis, at different points of time in the process. Different analysis techniques can require different types of models, or the same techniques may require different models to analyze the same goal at different stages of design. When creating a simulation model it is important to model appropriately the inputs based on the type of analysis, that can go from basic standard information to more complex and specific one. For example, in the early-stage energy model, one can use the program defaults for materials and operating schedules but for more advanced lightning model analysis it is necessary precise data on surface properties of the walls, floors, and ceilings. Often the initial model used for geometric studies is more detailed, and in a different form, than what is needed for the analysis, requiring some transformation. Also, file formats and conversions between different modeling and analysis tools can be an issue.

Geometric Analysis - managing building information

Before starting setting up the project and modeling the elements that will compose the BIMs one should first understand what is the goal of that model. The level of development and detail of the elements should be addressed so it helps understand what is really important for the building phase one is studying. Once the priorities and goals are established instead of studying everything it helps becoming more efficient, and with less cost than it would be if one tried to study and represent everything. Once the scope of the study is established it is necessary to understand how the building objects relate, what information is available and what information will need to be acquired.

When the model is being generated it is possible to study it through plans, sections, elevation and 3D visualizations, which makes it easier to understand and find conflicts or errors. Figure 3.14 shows a 3D section of a building competition executed at Grape Architects, that helped explaining the building levels organization and how a void in the middle of the building would function.

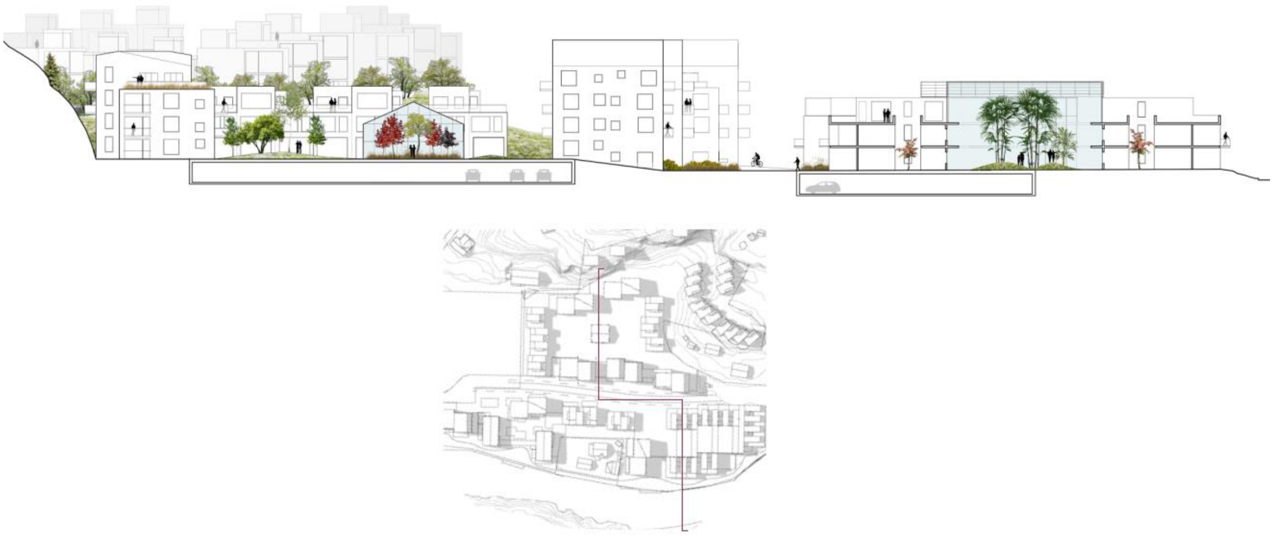


Figure 3.14- Section of a building competition. Source: image courtesy Grape Architects

The model plans (Figure 3.15) help understanding how spaces relate and the building organization. It is also possible to use 3D objects produced by furniture suppliers, adding the possible costs of each room regarding furniture. There are free online websites like Bimobject[27] that helps finding the visually and dimensionally correct object.

[27] https://bimobject.com/pt

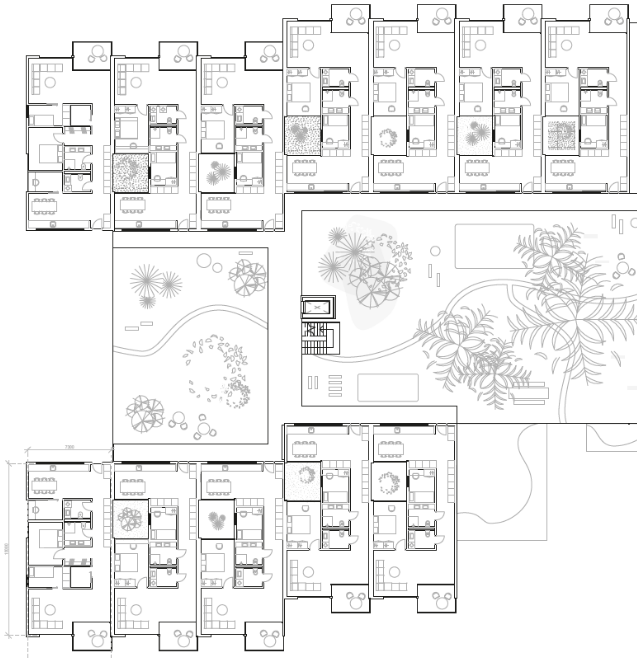


Figure 3.15- Floorplan of a building competition. Source: image courtesy Grape Architects

Bim tools for Architecture usage are usually represented by: *Autodesk® Revit® ; Bentley ; Graphisoft ArchiCAD; Allplan; Bentley AECOsim; Vectorworks ; Tekla Structures, Autodesk Civil 3D,* among others.

Massing and area studies

In the beginning of a project when there is an existing site is important to test how different building shapes, with different dimensions, especially heights, can influence the surrounds. The existence or nonexistence of public spaces, the connection or not with the existent objects, how it influences the sun on the buildings that already exist. Also if it is within the municipality building regulations for that site, including height and areas, or even what is the difference of areas with different shapes and connect that with efficiency of functions and cost. Figures 3.16 shows different volume studies, with different shapes and consequently areas, that are connected to the different building levels, on the same site. The A, B and C options show in the first two images the study of the volume shape and its integration with the surroundings, while the last image illustrate the building volume segmented by levels. It is from the area of the levels that quantity schedules are done, allowing to compare which volume will generate more area.

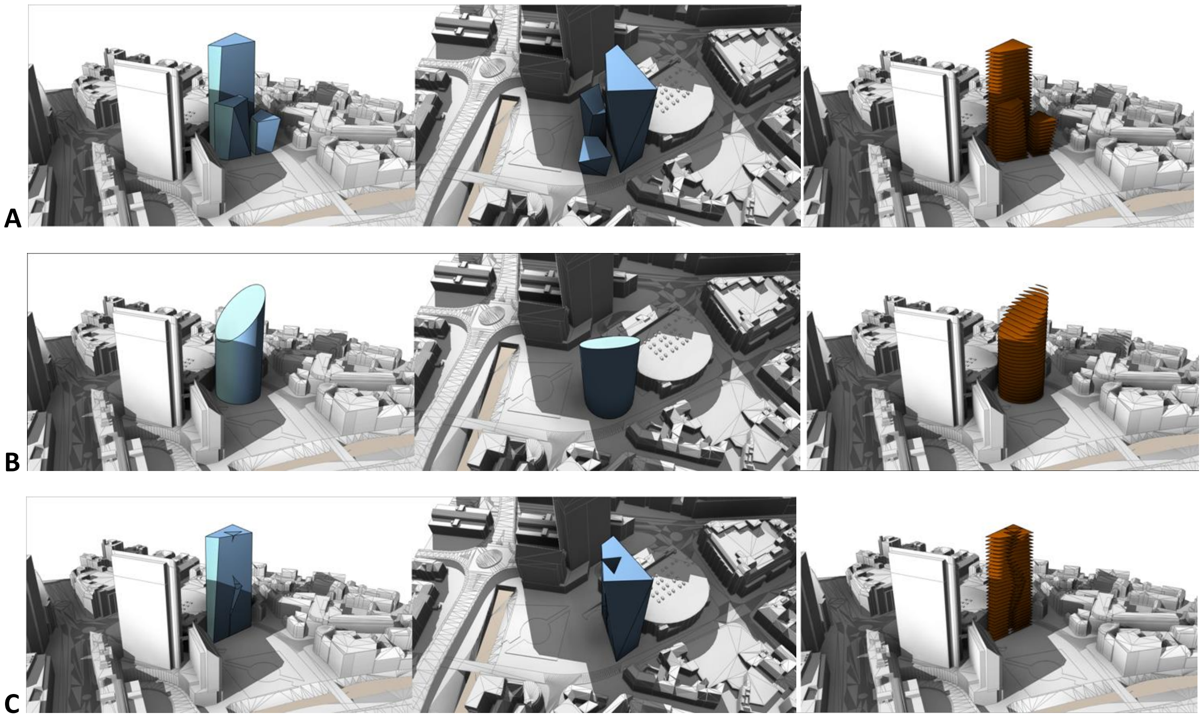


Figure 3.16 - Massing and area comparison between different design option studies. Source: Image courtesy Håvard Vasshaug from DARK Arkitekter presented at RTC2015

These studies are of major importance for competitions and when the project function scopus is being defined. Figure 3.17 shows the area for level of different housing typologies, represented by different colors. This analysis can be used by the owner to understand what the profit for selling a certain number of apartments and it is usually required when an architectural office applies to win a project in a competition.

ÅSSIDEN		BRA
Å_01	SMÅHUS I 3 PLAN	218,3
Å_02	SMÅHUS I 3 PLAN	218,3
Å_03	SMÅHUS I 3 PLAN	218,3
Å_04	SMÅHUS I 3 PLAN	218,3
Å_05	SMÅHUS I 3 PLAN	218,3
Å_06	SMÅHUS I 3 PLAN	218,3
Å_07	SMÅHUS I 3 PLAN	218,3
Å_08	SMÅHUS I 3 PLAN	218,3
Å_09	SMÅHUS I 3 PLAN	218,3
Å_10	SMÅHUS I 3 PLAN	218,3
Å_11	SMÅHUS I 3 PLAN	218,3
Å_12	SMÅHUS I 3 PLAN	218,3
Å_13	SMÅHUS I 3 PLAN	218,3
SUM		2 838

HAGEBYEN		BRA
H_01	REKKEHUS I 2 PLAN	123,8
H_02	REKKEHUS I 3 PLAN	160,3
H_03	REKKEHUS I 3 PLAN	160,3
H_04	REKKEHUS I 2 PLAN	123,8
H_05	REKKEHUS I 3 PLAN	160,3
H_06	REKKEHUS I 3 PLAN	160,3
H_07	REKKEHUS I 3 PLAN	160,3
H_08	REKKEHUS I 2 PLAN	123,8
H_09	REKKEHUS I 3 PLAN	160,3
H_10	REKKEHUS I 3 PLAN	160,3
H_11	PUNKTHUS 3-SPENNER	1044,0
H_12	PUNKTHUS 3-SPENNER	1044,0
H_13	REKKEHUS I 3 PLAN	160,3
H_14	REKKEHUS I 3 PLAN	160,3
H_15	REKKEHUS I 2 PLAN	123,8
H_16	REKKEHUS I 3 PLAN	160,3
H_17	REKKEHUS I 3 PLAN	160,3
H_18	REKKEHUS I 2 PLAN	123,8
H_19	REKKEHUS I 3 PLAN	160,3
H_20	REKKEHUS I 2 PLAN	123,8
H_21	PUNKTHUS 4- SPENNER	1213,0
H_22	PUNKTHUS 4- SPENNER	1383,0
H_23	PUNKTHUS 4- SPENNER	1213,0
SUM		8 563

ELVEBREDDEN		BRA
E_01	PUNKTHUS 4- SPENNER	1213,0
E_02	LAMELL	681,0
E_03	PUNKTHUS 3-SPENNER	1044,0
E_04	LAMELL	681,0
E_05	REKKEHUS I 2 PLAN	123,8
E_06	REKKEHUS I 3 PLAN	160,3
E_07	REKKEHUS I 3 PLAN	160,3
E_08	REKKEHUS I 2 PLAN	123,8
E_09	REKKEHUS I 3 PLAN	160,3
E_10	REKKEHUS I 2 PLAN	123,8
E_11	REKKEHUS I 3 PLAN	160,3
E_12	REKKEHUS I 3 PLAN	160,3
E_13	REKKEHUS I 2 PLAN	123,8
E_14	PUNKTHUS 3-SPENNER	1044,0
SUM		5 960

SIGNATURHAGEN		BRA
S_01	SENIORLEILIGHETER 3 PLAN ENDE	273
S_02	SENIORLEILIGHETER 3 PLAN	252
S_03	SENIORLEILIGHETER 3 PLAN	252
S_04	SENIORLEILIGHETER 3 PLAN	252
S_05	SENIORLEILIGHETER 3 PLAN	252
S_06	SENIORLEILIGHETER 3 PLAN	252
S_07	SENIORLEILIGHETER 3 PLAN	252
S_08	SENIORLEILIGHETER 3 PLAN ENDE	273
S_09	SENIORLEILIGHETER 3 PLAN	252
S_10	SENIORLEILIGHETER 3 PLAN	252
S_11	SENIORLEILIGHETER 3 PLAN ENDE	273
S_12	SENIORLEILIGHETER 3 PLAN ENDE	273
S_13	SENIORLEILIGHETER 3 PLAN	252
S_14	SENIORLEILIGHETER 3 PLAN	252
S_15	SENIORLEILIGHETER 3 PLAN	252
S_16	SENIORLEILIGHETER 3 PLAN ENDE	273
SUM		4 137

BRA TOTALT		21 498	
BRA-S TOTALT		19 882	8 %

Figure 3.17- Areas per type of housing. Different colors correspond to different house topologies. Source: image courtesy Grape Architects

3D Design Coordination analysis (spatial conflict, clash detection)

3D model coordination analysis detects conflicts between information, elements and different models, like structural models, architectural model, mechanical model, plumbing model, among others. It runs several tests in order to identify errors at different stages errors inside the same model and between models.

In the same model one can execute different kinds of coordination analysis tests. One can inspect the model elements like for example if the stairs meet landings in an appropriate and reasonable way, to improve the quality of the model and later errors and delays. Another coordination test can determine if the modeled elements match elements in the schedule. Since construction and installation of elements is normally performed based on the details in the schedule, this test is to see if the modeled dimensions match these scheduled dimensions. This test is performed by generating the schedules from the model and comparing them to the corresponding drawing schedules. One can test whether or not drawn elements are actually modeled. This can be done by printing the views from the model that match the drawing view and overlaying them. Tests if modeled elements connect and join in a realistic and accurate way can also be done. This test is performed by visually inspecting the model for unrealistic connection details. An example can be the checking if ceilings stop at the finished face of walls. Another example of what can be checked is if the fire rating element parameter matches the life safety plan ratings.

The coordination between different models usually compares elements, their position, dimension and number to see if there are any clash detection or if the model integrate harmoniously. Bim tools for coordination are usually represented by: *Autodesk® Navisworks® Manage, Bentley Navigator, Tekla BIMsight, Solibri Model Checker*

4D Scheduling Analysis

The 4D adds the time factor of the construction schedule to the 3D model. It is the ability to link the 3D parts or assemblies with the project delivery timeline, incorporating scheduling of resources and quantities, and modular prefabrication to support tracking and project phasing. In addition to collaboration, 4D simulations function as communication tools, used for verification, guidance and tracking of construction activities. Construction phasing simulation provides a tool that will help the construction team visualize logistical issues or inefficiencies, like out-of-sequence work or scheduling conflicts between multiple trades, optimizing the construction schedule. Bim tools for scheduling analysis are usually represented by: *Synchro; Vico; Autodesk® Navisworks® Simulate; Primavera; MS*

Project; Bentley Navigator; Autodesk® Navisworks® Manage; Bentley Navigator; Tekla BIMsight; Solibri Model Checker.

5D Cost Estimate Analysis

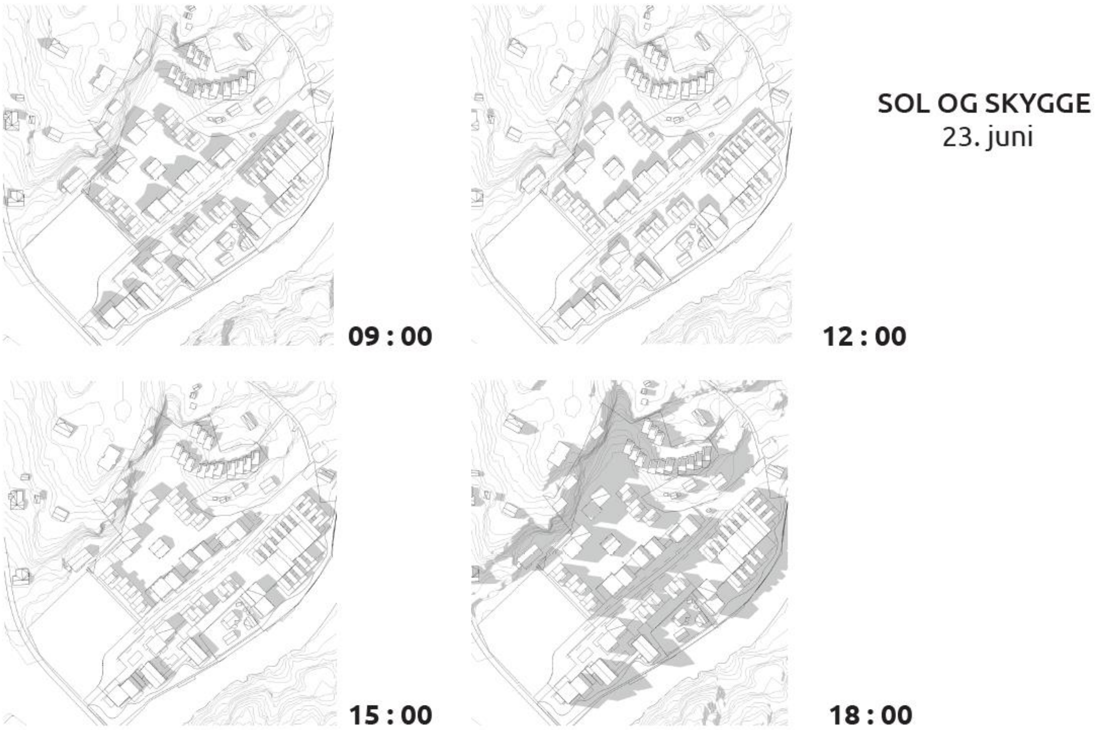
The 5D Cost estimate analysis is 4D scheduling analysis plus cost. It refers to the linking of 3D components or assemblies with schedule (time) constraints and cost-related information. Enabling the people involved/stakeholders of a construction project to visualize the progress of construction activities and its related costs over time. Through 5D cost estimate one can understand what happens to the schedule and budget when a change is made on the project; organize databases with cost and pricing information, labor productivity rates, among others; provide several iterative cost estimates.
on the right. For example, if dimensional parameters of an element changes, the associated schedules with areas, quantities, units and cost will update their information. Bim tools for Cost estimate analysis are usually represented by: DProfiler, Innovaya; Autodesk QuantityTakeoff (QTO); Exactal Cost X; Vico Office Takeoff Manager; iRIB Two.

Energy Analysis

There are several building energy simulations but in this thesis it will be outlined: solar shading, lighting visualisation, solar radiation. Bim tools for energy analysis are usually represented by: *Insign 360, Dynamo, Grasshoper, Green Building Studio; Autodesk Ecotect; EcoDesigner; IDA Indoor Climate & Energy Simergy; ArchiWIZARD; DesignBuilder; IES; Hevacomp; TAS.*

Solar Shading

Through solar analysis one can realize massing and orientation studies, understanding what will be the impact of the shades on the surrounding buildings. Usually these studies are done though the comparison of a massing and orientation design options in three different dates through the year (representing winter spring and summer conditions) at minimum of three different hours during the day, that represent the passage from morning to evening. Figure 3.18 shows solar studies on the 23 June at 09am, 12pm, 15pm and 18pm representing the average shades on site during a day in Summer. It can be observed that public spaces between the buildings will be pleasant, with few shade.



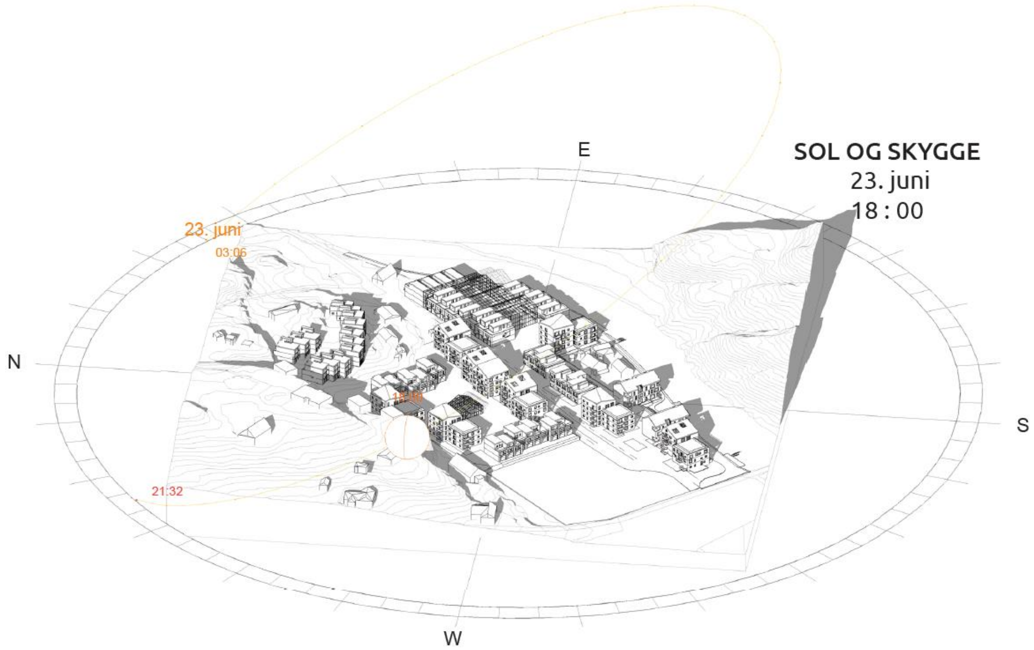


Figure 3.18- Study of site orientation and relation with shade study. Source: Image courtesy Grape Architects

Lighting Visualization

Massing and orientation are important design factors to consider for daylighting. Although it can be very difficult to get consistent daylight and control glare from east and west openings, this side of the building facing the sun's path can generally be easily shaded, while the opposite side facing away from the sun's path gets little or no light. This leads to the assumption that buildings that are longer on their east-west axis are better for daylighting and visual comfort. Daylighting can be studied by testing different combinations of possible length, height and, existence of building cutouts.

Figure 3.19 shows a shades study inside the building allowing to understand which areas will have more light and shadows, according to sun position.

Figure 3.19 - Shade analysis inside the building. Source: Image courtesy Håvard Vasshaug from DARK Arkitekter presented at RTC2015

One can understand and quantify the amount of the sun's light in a project with daylighting analysis. These can quantities differ: the farther a surface is from a light source, the less light reaches the surface and the darker a surface is, resulting in less incident light reflected. The amount of light reaching a surface is "illuminance" and is measured in lux (metric unit = lumen/m2). The amount of light coming from a light source is lumens, and the amount of light reflected off a surface is luminance (cd/m2). Less than 100 lux is considered insufficient daylight while between 100 lux and 2000 lux is useful daylight[28].

Figure 3.20 shows a graphic representation of a building illuminance floorplan at at 9am and 3pm, where we can observe with color blue the areas with almost no lux and yellow the areas with more lux quantity next to openings.

[28] https://sustainabilityworkshop.autodesk.com/buildings/measuring-light-levels

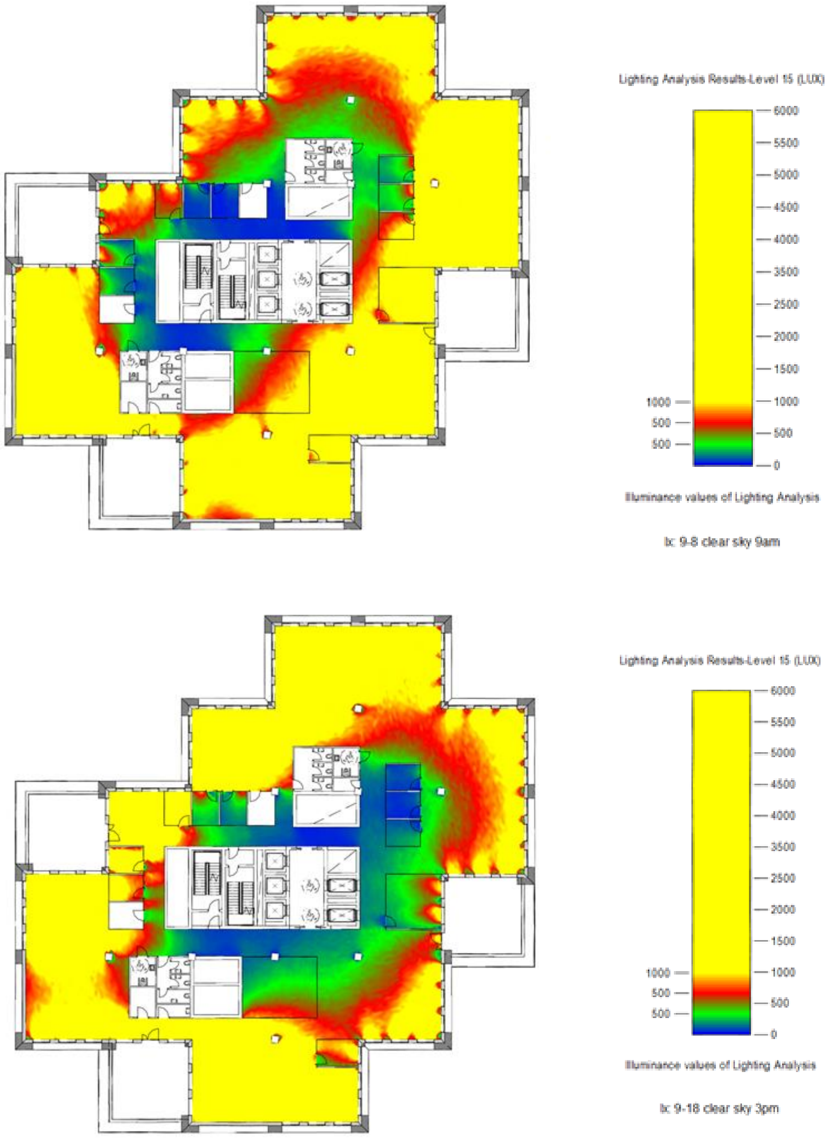


Figure 3.20 - Illuminance analysis. We can observe the darkest areas in blue representing the lowest lux values and from green, red and yellow the values closer to the building openings. Source: Image courtesy Håvard Vasshaug from Dark Arkitekter presented at RTC2015

Solar radiation analysis/solar load analysis

Solar radiation is the amount of solar radiation energy received on a given surface during a given time. In a building the radiation is absorbed through the facade and transmitted to the windows or reflected back. Values are usually in units of energy per area (W/m2) but they can also be quoted in terms of energy accumulated per day or per year (kWh/m2/day or kWh/m2/yr)[29]. One can understand and

[29] https://sustainabilityworkshop.autodesk.com/buildings/solar-radiation-metrics

quantify the amount of radiation with solar load analysis (solar radiation analysis). Energy loads are how much energy a building needs.

Software simulations can help understand how heating and cooling loads change throughout the year, and what elements of the building influence the values. In Figure 3.21 we observe that the lowest values correspond to parts of building that are obstructed by other geometries and consequently are in the shadow. This correspond to the parts in blue, the ones yellow correspond to the most heated parts.

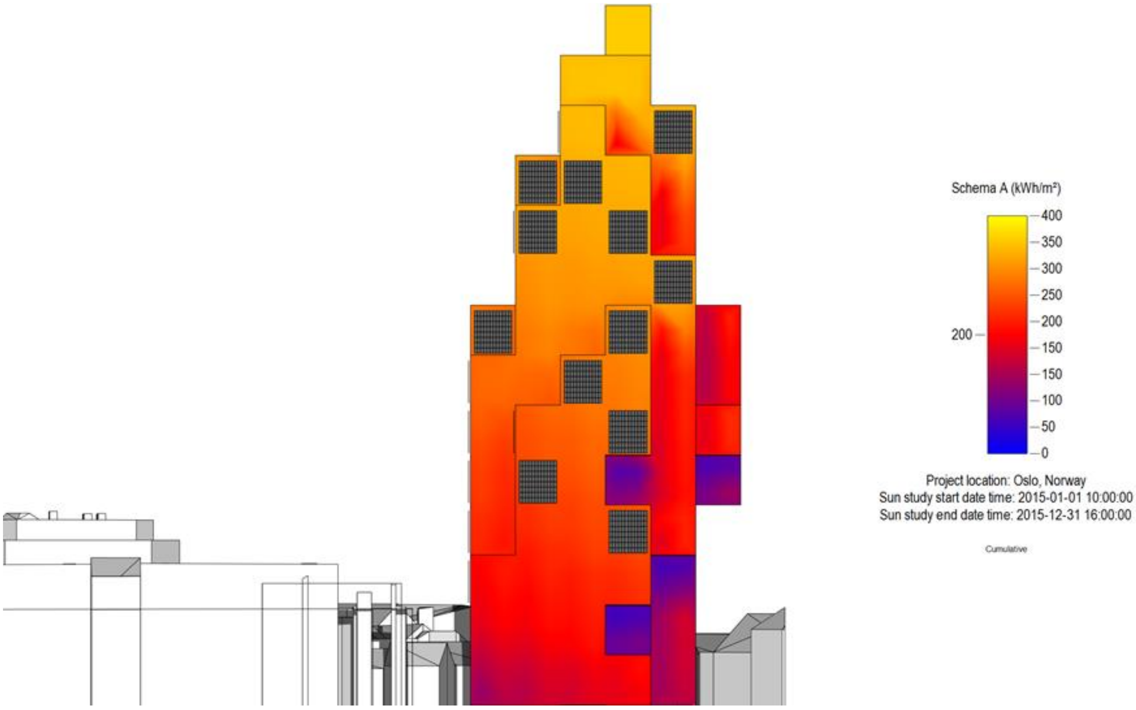


Figure 3.21 - Radiation analysis.Source: Image courtesy Håvard Vasshaug from Dark Arkitekter presented at RTC2015

Wind Studies

Simultaneously with massing and orientation analysis related to solar studies, understanding the wind performance and change building massing and orientation will minimize wind performance and improve the site's living quality. Figure 3.22 shows the windier areas in green and yellow and in blue the most protected ones. The analysis measures the wind direction and speed in m/s. This graphic analysis intends to show that the project construction will enhance site qualities in an area quite windy. We can observe in the left image the site without buildings and on the right image the site with buildings, and this change affects the wind behaviour, and the human comfort in site.

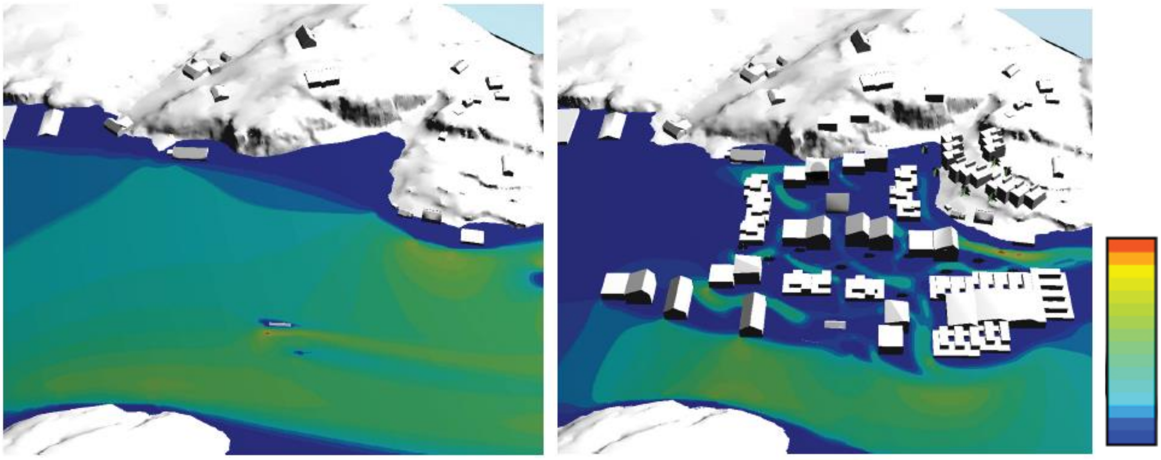
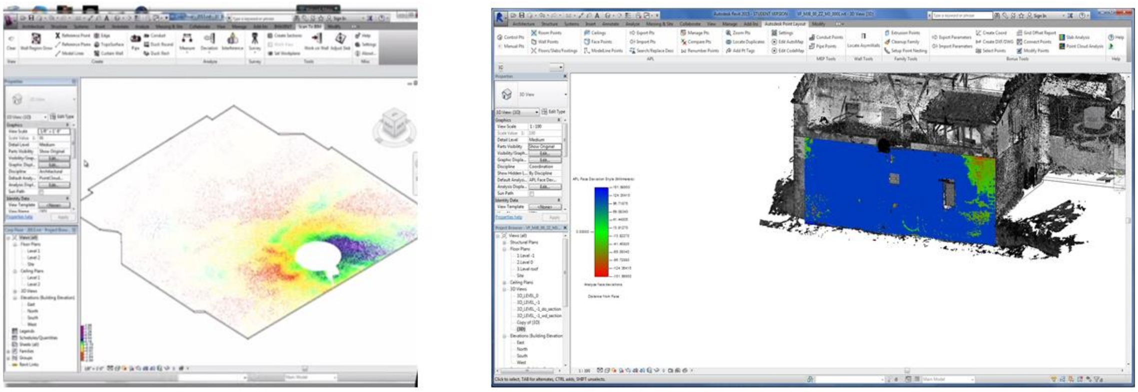


Figure 3.22- Wind study: Left image:without buildings; right image: with buildings. Source: Image courtesy Grape architects

Deformation Analysis

The deformation analysis described in 3.1.3. can also be done in BIM software. The PCM can be compared against orthogonal elements, like walls and floors, obtaining the deviation between the element and the points. Figure 3.23 shows the use of plugins like Point Layout[30] and Scan To Bim[31] for the deviation/deformation analysis.



'SCAN TO BIM'* plugin for *Revit ***'POINT LAYOUT'* plugin for *Revit***

Figure 3.23- Element deformation analysis

[30] https://www.autodesk.com/products/point-layout/overview

[31] https://www.imaginit.com/software/imaginit-utilities-other-products/scan-to-bim

3.3. Conclusion

In this thesis, BIM is considered a process of structuring and analysing information. BIM allows to understand geometry while the elements are being created; understanding how spaces and elements relate and to know the object in study. One virtually generates the object in study, which requires profound knowledge of the building or object. Following the 3D model generation, multiple analyses can be made. These include quantities and cost estimation analysis from selected elements, clash detections and coordination between several models with different data (for example checking the architectural model with the structural model from engineers); energy analysis, wind and solar studies, life-cycle analysis (LCA), deformation analysis, and so forth.

Understanding a building involves several experts from distinct areas, like architecture, engineering, geology, topography, conservation, and others. The merging and management of the information obtained by all specialists can be done through models of structured information. These models work as simulations or virtual representations of the reality, allowing to visualize, manage and analyze the building information. According to Cóias (2006), the study and assessment of an existing facility and its surroundings is based on the creation or application of a model, with the required accuracy. The information collection, of a facility and its surroundings, is established by the model's creation and development needs.

When studying a building the next step after acquiring and processing data is to analyse the information. There are different types of analysis. Analysis of the current state of building through point cloud structured data: material analysis through radiometric studies, material temperature analysis through infrared thermography studies and, building deformation analysis; geometric studies. In addition or besides the point cloud data analysis one can perform BIM analysis to study how to enhance the project performance and solution. BIM processes use different kind of software to interpret and digitally record physical and functional characteristics of the as-built environment. BIM manages building information linking it to 3D elements; this also means every tool involved on this process is part of BIM. Not only the typical AEC software like Autodesk® Revit® and Archicad, but also tools like management software and programming software, among others. BIM tools connected should contain the following core features: parametric model, bi-directional associativity, intelligent modelling, interoperability, collaboration features.

Different BIM analysis techniques can require different types of models, or the same techniques may require different models to analyze the same goal at different stages of design. BIM allows geometry understanding since it is necessary a profound knowledge to do generate building elements. Following the 3D model generation, there are multiple analysis one can do. These include massing and area studies, 3D design coordination analysis, 4D scheduling analysis, quantities and cost estimation analysis, energy analysis, wind and deformation analysis, among others

BIM benefits resulting from this analysis processes are the improved information exchange, interoperability, elimination or reduction of unbudgeted changes on projects, increase of quantities and cost estimation accuracy, clash detections which provide time and cost savings, reduction in re-works due to enhanced quality control and design coordination, enhanced data management, quality assessment and reporting tools.

BIM limitations are usually connected to software and hardware limitations as well as change adoption by the people involved. There is a need for development of greater interoperability between software, need to implement the industry standards, and improve handling very large model files sizes and complex techniques for sharing information. There is also a need for the implementation of data and workflow standards when generate and structuring information in BIM analysis. One of the reasons why standards are needed is to structure and improve the collaboration not only with outside parts but also inside office. Data and workflow standards in a practical way are very hard to implement daily, resulting in confusing data and workflows which reduce the quality of communication and project outputs. In the next chapter, BIM usage for new buildings and respective standards will be outlined as a guideline to implement the use of BIM processes and standards for existing buildings interventions.

4

Standards and BIM usage for existing building interventions

This chapter is directly extracted and adapted from our journal paper "Towards increased BIM usage for existing building interventions" published in Structural Survey, Vol. 34 Issue: 2, pp.168-190, (doi: 10.1108/SS-01-2015-0002).

In this chapter we first look, in Section 4.1 and Section 4.2, into the way BIM standards, for new constructions, are typically structured, relying intensively on literature review. We focus primarily on the guidelines and BIM standards that aim at achieving a better second level BIM collaboration or an initial third level BIM collaboration. These standards consider quite closely the recommendations offered by OpenBIM BuildingSMART, as this is the standardization body behind the standards needed for BIM Level 3 collaboration. In Section 4.3 to 4.5, we then consider the challenges of applying BIM processes for intervention projects in existing buildings, hereby relying on literature study (mainly the overview article by Volk et al., 2014), and our own experiences regarding the usage of BIM in existing building interventions. Finally, in Section 4.6, we propose the usage of BIM guidelines tailored to the modeling of existing building interventions, and we indicate why such guidelines would be of help in such intervention projects for existing buildings. Figure 4.1 illustrates a schematic diagram of the Chapter 4 subjects summary.

Figure 4.1- schematic diagram of the Chapter 4 subjects summary

4.1 The benefits of standardized workflows in the construction of new buildings

The architecture, engineering and construction (AEC) industry heavily depends on collaboration, having different teams communicating among each other through the building life-cycle phases. For each of these teams, there are different nomenclatures, vocabularies, geometries, accuracy requirements, computing paradigms, data formats, and so on. These teams typically come together in a building information modeling (BIM) environment (Eastman et al., 2011; Smith and Tardif, 2009). In order to smoothen the collaboration among them, inside and outside the BIM environment, it is important to define BIM standards for information exchange on which the teams in an AEC project agree (Nawari, 2012). BIM standardization, namely, guarantees an agreed form and quality of information, enabling the information to be used and reused among the partners that agree upon the standard (BSI, 2013). Through standardization, it is possible to make processes and products interchangeable, thereby allowing to identify those processes and products with optimal parameters and to consequently reduce variety and its associated high costs. BIM standardization is intended to meet the needs of users, focussing on compatibility and contributing to a better communication and understanding (Allen and Sriram, 2000; UNIDO, 2006).

BIM standards are compiled in the form of guides, protocols, and mandatory regulations. Guidelines consist of recommended, non-mandatory controls that help support standards. They are descriptive and optional documents that should be viewed as best practices. Protocols are prescriptive and optional documents, defined as a set of steps or actions to assist workers in implementing standards and guidelines. Mandatory regulations are prescriptive and mandated by an authority (Kassem et al., 2013), consisting of requirement/specification documents with sets of prerequisites that must be fulfilled. BIM standards can be formalized as any of these document types, or as a combination of them. These documents then describe processes, procedures, and requirements that can be (optionally) or must be (mandatory) followed for the development of BIMs. By following these documents, AEC stakeholders are able to produce, release, and receive information in a consistent format, resulting in an efficient information exchange and compatibility between project disciplines in BIM deliverables.

4.2. BIM standards for new buildings

Developments in BIM standards differ from country to country. In some countries, BIM adoption and BIM standards are in fast development: BIM guidelines are not only available, they are also rapidly becoming mandatory for public projects. In other countries, the usage of BIM is not yet even promoted, let alone guided or required. The levels of BIM usage can be observed in Figure 4.2.

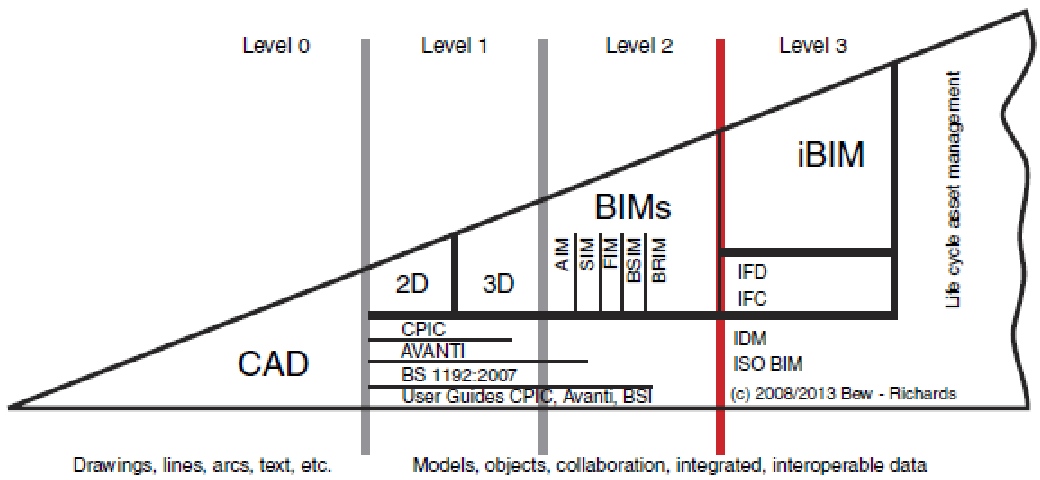


Figure 4.2- The levels of BIM usage display an aspiration to achieve a particular level of collaboration or information exchange. Source: Image courtesy Bew and Richards, as declared in BSI, 2013 page vii

There are governments or public institutions that already require the use of BIM for publicly funded building projects, examples are USA (GSA, MAP-21), Hong Kong (Hong Kong's Housing Authority) South

Korea/China (Public Procurement Service), the Netherlands (Rgd BIMnorm), Denmark (Danish Enterprise and Construction Authority), Finland (Senate Properties), and Norway (Statsbygg). The UK (UK Government), Sweden (Public Companies: Akademiska Hus, Fortifikationsverket, Riksdagsforvaltningen, Specialfastigheter Sverige and Statens Fastighetsverk), Singapore (BCA), Australia (BuildingSMART Australasia), Belgium (ADEB-VBA), France, and Germany are in the process of implementing and advising or enforcing the use of a BIM standard (often in the form of an advisory "guideline" document. Furthermore, the European parliament has recommended the adoption of electronic tools, such as BIM, for publicly funded building projects in the EU by 2016 (see also CEN/TC 442CEN, 2015). So, the development and implementation of BIM standards by national construction companies and architectural design offices is rapidly evolving in various countries.

In this section, we outline what is typically included in existing BIM standards, in order to identify the common framework and content that should be taken in account when considering BIM standards for interventions in existing buildings. We distinguish here between the standardization of BIM data exchange requirements, and the standardization of modeling representations within BIM applications.

4.2.1 Data exchange requirements in BIM standards

In terms of data exchange requirements, BIM standards commonly formalize best practices for the representation of data, of data exchange requirements, and of overall design process requirements. These best practices are commonly represented around one or more swimming-lane types of Business Process Models. The available data sets and corresponding stakeholders in a design and construction project are typically first identified. Then, the standards represent the data sets in a hierarchical format, thereby explicitly linking the distinct taxonomies used in the various data sets. These two steps allow to clearly and unambiguously formalize specifications on: how BIMs should be modeled; how BIM data should be exchanged (BIM deliverables); and how collaboration should occur in the overall design and construction process.

The eventual aim of the BIM standards thus falls apart in three key goals: formalizing the data sets, formalizing the exchange requirements, and formalizing the overall process model. This structure is compliant with what is typically considered as the three fundamental components for a reliable computerized information exchange (Nawari, 2012; NIBS, 2012): (1) standardized formats for information exchange; (2) standardized understanding of what the information exchange really is; and (3) specification of which information to exchange and when.

(1) Formalizing the data sets

BIM environments rely on formal schemas for the definition of the information that they process. Only if these formal schemas are in place, data exchange is possible. A schema requires a consistent and structured set of object names. Each object name should have its meaning defined and the units in which it may be expressed attached, so that the name contributes to a controlled vocabulary of construction terminology (NIBS, 2012). If the central schema is agreed upon by many stakeholders, a standard schema is in place and a broader data exchange can be organized.

A first clear example of a formal schema for the definition of building information is the OmniClass Construction Classification System. It consists of 15 classification tables that incorporate formats, terminology, and concepts of the built environment and processes used to create it (NIBS, 2012). This taxonomy targets large scale standardization over the entire world. The industry foundation classes (IFC) data model is a second example classification schema for the specification of building elements. IFC allows to represent building information modeled in BIM software applications. The IFC schema is developed and maintained by BuildingSMART International and it relies for its definition on the ISO 10303 standard, also known as the "Standard for the Exchange of Product model data" (STEP) (ISO, 1994). The ISO 10303 or STEP standard includes the specification of its own data modeling language, namely, EXPRESS (ISO, 2008). Similar classification schemas are the ISO-15926 standard (ISO, 2013) and the CIMsteel Integration Standard Version 2 (CIS/2). What IFC does for building data, ISO-15926 and CIS/2 do for industrial data and steel data, respectively, namely, providing a mechanism for describing building/industrial/steel data throughout the life cycle of a building/ industrial product/steel product, independent of any particular software system (Eastman et al., 2011; Bregianni, 2013).

The BuildingSMART Data Dictionary (bsDD) is an effort that extends the original standardization efforts, in order to be able to capture as much as possible relations among different standardization schemas. The bsDD aims at accommodating equivalences of construction-related terms between different languages (English, Dutch, Spanish, Portuguese, and so forth). The bsDD is based on efforts made earlier in the work toward an International Framework for Dictionaries, which was standardized into the ISO 12006-3 standard (ISO, 2007). The bsDD is an open terminology standard, where concepts and terms are semantically described and given an unique identification number using a Globally Unique Identifier (ISO, 2007). The generic description of a particular concept specifies the synonyms, a definition, and relations to other terms. Using this description, one is not only able to: specify data according to the definition of a particular concept, one is also able to; translate one concept specification to an equivalent concept specification as it is used in other countries with a different language (e.g. Spanish vs English); or to correctly identify how a particular concept relates to other concepts. The bsDD concept goes beyond the idea of a regular classification schema, such as OmniClass, in the sense that it allows to specify the meaning of a concept not in one structure, but in many different structures at the same time.

(2) Formalizing the exchange requirements

Modeling software vendors establish very diverse tools for exchanging information. Information exchange occurs through application programming interfaces, proprietary data formats (e.g. RVT, DGN, DWG), or non-proprietary data formats (e.g. IFC, OmniClass). This information exchange needs to be formalized in a proper BIM standard, because it takes place at various levels and stages, from building design to construction and demolition. It is not necessary, not even desired, to exchange all available information from one BIM project stakeholder to another in every stage of the project. Rather, only a portion of the information is exchanged, while still using an agreed upon data format. BIM guidelines typically recommend to conceptualize project-specific exchange agreements between project partners at the very outset of the project. In setting these agreements, project-specific contractual bindings need to be set, so that it is clear which partners carry responsibilities for which tasks during the entire project. It is imperative for a project team to carefully devise these project-specific agreements in order for any BIM-based project (e.g. BIM Levels 2 or 3) to become a success for all partners involved. National BIM standards or guidelines only seldom give specific recommendations regarding this part of the exchange requirement formalization.

What is clearly outlined in any BIM standard, is the need for an exchange of subsets of the original complete building specification, which can be in IFC, for example. When considering the BIM Level 3 type of collaboration (Figure 1), this is the core reason behind the development of the model view definition (MVD) concept (BuildingSMART International, 2014). In short, an MVD captures a subset of a complete model. For example, when building an MVD on top of the IFC data model, it will define a subset of the IFC schema providing implementation guidance for all IFC concepts, like classes, attributes, relationships, property sets, quantity definitions, used within this subset (Eastman et al., 2011). So, an MVD shows the software implementer which IFC elements to use, how the implementation should function, and what results are expected.

The MVD concept and tools are developed and maintained by BuildingSMART. A number of examples can be found in the work done in the context of Construction Operations Building Information Exchange (COBie) (East and Carrasquillo-Mangual, 2012). COBie originally aimed to specify how the required information can be subtracted from BIMs so that it is usable for FM. One type of information that is typically excluded in a COBie, is geometrical information, which is often not a requirement for FM. COBie hereby relies on existing data representation formats, including XML and IFC. COBie can thus be considered as an example MVD focussing specifically on FM.

(3) Formalizing the overall process model

After specifying the available data sets and the way in which they should be exchanged, a BIM standard for information exchange typically also needs to consider the overall process model. If we remain to consider primarily the standard methods that are proposed by BuildingSMART, this should be handled by an information delivery manual (IDM). An IDM is a textual report with a main visual flow graph that consists of descriptions of BIM workflows, processes, roles, and software for specific uses of the exchanged models. It describes where a process fits and why it is important, what information is created, what this information is used for, whom the information users are, how and when the BIM information is exchanged, and how it should be supported by software solutions (Wix and Karlshøj, 2010).

Most BIM standards make abstraction of the language in which this overall process model is constructed, not “limiting” themselves to IDM, for instance. In these cases, the BIM standards and guidelines include one or more swimming-lane diagrams that indicate best practice or ideal versions of what a “traditional” building process model should look like. This can then be used as a basis in setting up a project-specific building process model that is formalized in conjunction with a set of exchange requirements and contractual agreements.

4.2.2 Data modeling requirements in BIM standards

Whereas data exchange requirements focus on guidelines for the overall collaborative design process, the data modeling requirements focus primarily on the content of this process: what content needs to be modeled in the BIMs and to what degree. Traditional BIM standards and guidelines tend to remain relatively vague about the actual content that needs to be modeled in the diverse tasks of the overall process model. There can namely be great differences between modeled content depending on project type and context (people/companies involved).

The concepts Level of Information Detail (LID) and Level of Development (LOD), on the contrary, are often very central in any BIM standard or BIM guideline. The Level of Information Detail (LID) is how much detail is included in the model element and can be thought of as input to the element. While Level of Development (LOD) is the degree to which the element's geometry and attached information can be relied upon by users when using the model and can be thought of as output (BIMForum, 2015). LOD essentially captures the quality of detail that is included in the representation of the building element. The difference between a LID and a LOD thus lies in quantity versus quality.
AEC (UK) (2015) states that elements should be graded according the level of graphic detail:

- ❑ Component Grade LOD1 – Symbolic (Symbolic placeholder)
- ❑ Component Grade LOD2 – Conceptual (placeholder with minimum level of detail
- ❑ Component Grade LOD3 - Generic – Defined (approximate dimensions)
- ❑ Component Grade LOD4 - Specific (accurate dimensions)
- ❑ Component Grade LOD5 – For Construction / Rendering (detailed, accurate and specific element)
- ❑ Component Grade LOD6 – As Built (precise modelled representation of the building element)

AEC (UK) (2015) considers the graphical appearance completely independent to the non-geometric information linked with the element. This means an element can have a Grade LOD1 (Symbolic) graphical representation attached with the manufacturer's data, cost and specification information.
Five standard LOD levels have been suggested by the AIA (2013):

- ❑ LOD100 (not modeled): an element may be described as a symbol or as a generic representation;
- ❑ LOD200 (generic): an element is graphically represented as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation;
- ❑ LOD300 (specific): an element is graphically represented as a specific system, object, or assembly with specific size, quantity, shape, location, and orientation;
- ❑ LOD400 (manufacture/install): an element is graphically represented as a specific system, object, or assembly in its size, quantity, shape, location, and orientation with detailed fabrication, assembly, and installation information;

- ❑ LOD500 (as-built; operate/maintain): an element is a field-verified representation in terms of size, shape, location, orientation, and quantity.

All the content requirements and authorized uses must be fulfilled for a model element to belong to a specific LOD. When starting a construction project and setting up a project-specific exchange process model (see previous sections), project participants are meant to define the LOD that they want to achieve for model elements at all (exchange) stages of the building project. Any milestone model deliverable will then contain a combination of model elements at various LODs (Vandezande, 2013). The BIM standard or guideline typically provides a number of guidelines on which levels of detail and LOD are typically achieved at various stages in a project.

4.3. Toward collaborative workflows in interventions in existing buildings

The situation is different for interventions in existing buildings (rehabilitation or refurbishment). BIM applications are rarely used in such contexts. Hence, the usage of existing BIM standards is not naturally considered. Yet, the availability of any kind of standardized workflow (e.g. a BIM standard) might bring about improvements to the workflows of interventions in existing buildings that are at least equally important for this industry as they are for the “regular” construction industry. In fact, the usage of such standards could prove to be a lot more important to this domain, as an intervention in an existing building often includes a greater number of data sources that need to be consulted on-site (original building structures, original drawings, specific material types, neighboring, and in-house structures), in addition to an equal number of project partners (client, construction company, architect, subcontractors, local authorities).

A rather obvious reason for the limited use of BIM for existing buildings is the lack of an incentive. As long as traditional workflow deliverables are required for intervention projects in existing buildings, a significant part of the industry sees no real need for starting to model existing buildings in a complex BIM software environment. Even if BIMs are used to construct the building, its usage usually ends after construction. In some cases, a transition of information is included from the BIM environment to a facility management (FM) environment (East and Carrasquillo-Mangual, 2012). Yet, this FM environment typically contains only a part of the information available in the original model. As a result, BIM is typically not available at the outset of an intervention project in an existing building.

Most interventions in existing buildings start from the building site survey, which is usually quite expensive and labor-intensive. As it is not a natural reflex to turn this into a BIM in the course of the project, for instance at the tender phase of the intervention project, collaboration often remains to occur in an ad hoc manner, which is far off from the standardized workflows that are currently reshaping the regular construction industry, and which results in considerable costs for the intervention projects at stake.

4.4. Addressing challenges to improve usage of BIM for existing buildings

The main challenges hampering progress in BIM implementation for existing buildings are outlined by Volk et al. (2014): (1) high modeling/conversion effort from captured building data into semantic BIM objects; (2) updating of information in BIM; and (3) handling of uncertain data, objects, and relations in BIM occurring in existing buildings.

These are critical barriers and challenges, which we encounter as well in our research on the usage of BIM software for existing buildings. None of these challenges is particularly "easy to deal with." For example, it is indeed a time-consuming process to manually model an existing building into a BIM environment. Although some strategies have been presented to fasten this process and make it more accurate, they typically also require a lot of manual efforts. An example strategy is to use laser scanning or photogrammetric tools (for building surveys) associated with BIM tools, perhaps including some semi-automatic or automatic shape recognition functionality. This strategy still requires considerable manual efforts, and, there is an additional hardware and software cost. It appears that, if one wants to obtain qualitative BIMs, one cannot simply expect it to come there effortlessly. Also, the continuous updating of information during the different phases of the building life-cycle is something that requires manual effort, no matter from which perspective you look at it. Finally, handling uncertain data can be done to some extent, but it requires specialized workers that interpret building data and properly integrate it in BIMs.

Also, the regular construction industry has benefited from technological advances and automatic procedures, such as BIM. But, also in this case, a lot of manual work is still required in the overall workflow in any project. To further improve collaboration in such projects, reliance on BIM standards and guidelines is advised. Such guidelines, namely, provide the means to agree upon and streamline the way in which information is consumed and passed on throughout the entire construction project.

By relying on this basis, a lot of the manual work can be done more efficiently. Following the same line of thought, workflows are likely to be improved for interventions in existing buildings as well when relying on BIM standards and guidelines. The emergence of such guidelines might then further stimulate the usage of BIM technologies in this field.

The present thesis thus assumes that some progress can be made by minimizing the amount of effort one has to make in creating and managing BIMs for existing buildings. Minimizing this effort might be achieved by setting and using appropriate BIM guidelines for modeling existing buildings. Through guidelines, one might be able to set some point of reference on how to build an initial model for an existing building, specifying what kind of information (not just geometric) should be included from the 3D building survey into the initial BIMs, and to what level it should be developed. These guidelines should promote an editable parametric model, and the deliverable information and formats should also be defined. These guidelines can then help in further addressing the challenges outlined by Volk et al. (2014), which would hopefully lower the threshold between added value and lacking incentive in the application of BIM environments for interventions in existing buildings.

4.5. BIM for existing buildings

Section 4.2 entirely introduced how the existing BIM standards and guidelines can be used in mainstream construction projects. At the moment, such standards are seldom used in any intervention in an existing building. This is primarily caused by the limited use of BIM in this particular field, which is in turn caused by the barriers outlined by Volk et al. (2014). In this and the following section, we question the application of BIM and of BIM standards to interventions in existing buildings (rehabilitation and refurbishment), thereby focusing on the main challenges outlined by Volk et al. (2014).

4.5.1 Documenting existing buildings using BIM software

The usage of BIM has been suggested for the documentation of existing buildings in a cultural heritage context. In this case, the building is typically modeled based on historical documents and on-site surveys (Pauwels et al., 2008). Architectural BIM software, such as ArchiCAD and Autodesk® Revit® , has been deployed in an architectural heritage context (Pauwels et al., 2008; Murphy et al., 2005; Fai et al., 2011), but there is still a lot of work to be done concerning the appropriated platforms, techniques, and usage of these virtual heritage artefacts. In many cases, these historical BIMs are mainly constructed with a more theoretical purpose, namely, as a way to study the historical value of any particular building. BIM software could play an important role also in the rehabilitation and refurbishment of existing buildings. BIM software can namely bring the advanced features that are also relied upon when modeling a new construction, namely, project alternatives calculation, digital cost estimation, quantity take-off, data management, as-built documentation, reporting tools, quality assessment, vulnerability and collapse analysis, deviations or deterioration analysis, deconstruction execution planning, and so forth.

Especially when the existing building is managed using FM tools, it should be relatively straightforward to connect the information in the FM application to a BIM application and use the latter for the intervention project. Ideally, a new building would then be constructed using a BIM application, after which the information would then be passed on to an FM tool (perhaps via the COBie tool of East and Carrasquillo-Mangual, 2012), and after years of maintaining both the building in the FM tool and the building itself, a BIM application would then again be used, relying on the original basis in the FM tool, to devise the intervention project. This kind of process (BIM→FM→BIM) would fit in well with the statement made by Sheth et al. (2010) that the development of technologies, tools, building regulations, and standards leads to the increase of building intervention management efficiency, which in turn increases building life-time (see also the BIM-BAM-BOOM keynote by MacLeamy, 2014). When no BIM→FM→BIM scenario is possible, in-depth building surveys are typically performed before starting to plan an intervention project.

4.5.2 Challenges and obstacles toward the application of BIM software

Whichever documentation scenario is followed (BIM→FM→BIM or not), there is still no methodological recipe for managing existing building intervention projects based on BIM models. There are a number of challenges and obstacles that need to be taken into account in this regard. To document these, we will hereby rely on the “major challenges and areas of research” in modeling and using BIMs for documenting existing buildings as they were previously identified and outlined by Volk et al. (2014): (1) the handling and modeling of uncertain data, objects and relations occurring in existing buildings in BIM; (2) the high modeling/conversion effort from captured building data into semantic BIM objects; and (3) the update and maintenance of information in BIM.

(1) Uncertain data, objects, and relations

Based in Volk et al. (2014) and in our experience, the presence of uncertain data and unclear or hidden information hinders as-built BIM adoption. There is a high level of uncertainty about the features that need to be included in the BIMs in order for them to correctly represent the existing buildings. For example, what are the layers of materials of an existing wall, how are different (in some cases invisible) elements assembled, and so forth (see also the learning phase in Pauwels and Di Mascio, 2014). These are crucial pieces of information that need to be taken into account in any intervention project for an existing building, yet they are seldom known beforehand.

Uncertain data can be the output of an incomplete survey resultant from miscommunication, incorrect tools, bad planning, etc. It can also result from an incorrect processing technique or the absence of culling unwanted data. Unclear or hidden information can result from site conditions or be part the elements inside layer materials. Volk et al. (2014) considers hidden information as one of the major obstacle in the as-built BIMs generation. While we agree it this statement, we also consider the acquisition workflows and their output data could improve when used for modeling. The case studies in the present thesis will focus mostly on uncertain data and unclear information.

There are diverse alternative approaches toward handling these uncertainties. A first option is to make assumptions about this kind of hidden information and leave it to that, as was done by Pauwels and Di Mascio (2014), for instance. As a second option, one may choose to annotate the building element with the associated levels of uncertainty or "fuzziness." In that case, decision making can at least take into account these levels of uncertainty. A way to do this, is to use the LOD and LID concepts while modeling building elements. We propose to use the term LOD for existing buildings identically to how the term is used in existing BIM standards for new buildings. These levels indicate the amount of detail and information that is or should be included in a BIMs (nuts and bolts included, or limiting to beams, floors and walls). We propose to associate with the LOD a new term, namely, level of certainty (LOC), to be added whenever the term better reflects the content and purpose of these levels within existing buildings. Namely, LOC need to reflect how (un)certain a modeler is about the extent to which his model is identical to the existing situation (LOC 100 very uncertain – LOC 500 absolutely verified).

The present thesis and its case studies rely on the use of LOD suggested by the AIA (2013). We consider the described Level of Information Detail grades too complex to merge with the LOD in the refurbishment intervention. Alternatively, we recommend the use of the above suggested LOC term associated with the LOD whenever the BIMs element requires it.

Regardless of the way in which an existing building is modeled, there will be a difficulty in preserving the correspondence between the model and the existing structure. Keeping a model in-sync with the actual existing building requires people who are highly skilled in information modeling itself. The modeling decisions, about exactly what elements to model and how to model, are inherently subjective and qualitative of kind, resulting in a model of variable quality and structure.

In Figure 4.3, we can observe what such modeling decisions can result in for a door example. The right half of the Figure shows the original 3D point cloud, and the left half shows the resulting 3D model. We can observe that the 3D model is a simplification of the point cloud, and that it is the result of an interpretation of what information is important.

Figure 4.3. An example of how an original point cloud can be interpreted into a 3D object, giving an impression of the kinds of simplifications and interpretations that are typically made

This is a first important place where a BIM standard or a BIM guideline for existing buildings can provide actual and explicit benefit to anyone who aims to challenge these issues of uncertainty. Namely, modeling the BIMs from the point cloud data and the otherwise obtained survey data is a labor-intensive task. If a set of BIM guidelines can outline which decisions and options are central in starting to model any existing building from the survey data, there would at least be some reference point to start from, as well in the case of making assumptions as in the case of naming uncertainty levels. In these two alternative routines, recommended procedures should be included in the BIM guideline for modeling the existing building, so that the BIM modelers and survey companies can agree before the outset of the project which data they will produce, when and how they will exchange it, and how the overall process occurs (swimming lanes). An important addition to the existing guidelines for traditional construction projects, is the inclusion of a table that records LOC or uncertainty, which could be devised similar to the LOD 100 – LOD 500 table.

(2) High modeling/conversion effort

A second boundary to BIM adoption for existing buildings is the amount of modeling/conversion effort required to obtain a useful model (Volk et al., 2014). This statement is also made by Huber et al. (2011): BIM creation is an issue of critical importance for BIM usage and development for existing building interventions. As already indicated, manually modeling the BIMs requires highly skillful people, lots of time, money, and an experience in handling uncertainties.

To address this “manual modeling effort” challenge, it has been suggested to use TLS and ADP technologies when making building surveys. However, the large amount of data and the unwanted noise can make an appropriate interpretation and usage difficult, thereby hindering automation techniques. Figure 4.4 shows an image of a point cloud that has unwanted data blocking the visual connection with the element in study.

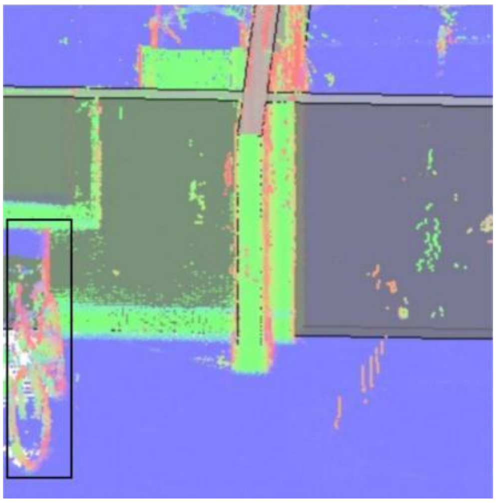


Figure 4.4- Unwanted noise (bike) in a point cloud survey. Source: image courtesy Dark Arkitekts

Figure 4.5 shows an example of a lack of building information in the 3D survey. More precisely, the 3D points for the roof are missing due to the impossibility of accessing it for its survey. These occasional lacks can be complemented with photos and field annotations, among others, but manual interpretation and modeling is required in all cases, which again requires considerable effort (see “modeling phase” in Pauwels and Di Mascio, 2014).

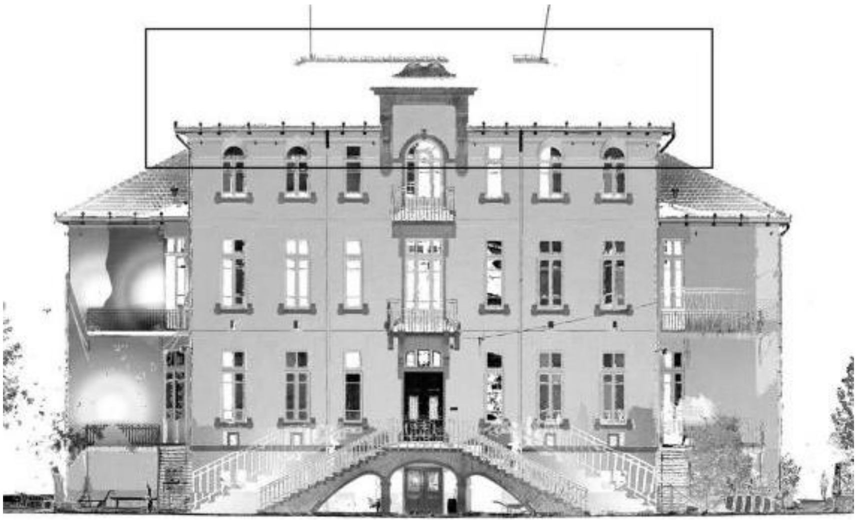


Figure 4.5- Lack of information (roof) in the point cloud. Source: image courtesy ArcHC_3D

In such manual efforts, point cloud data are most often used as templates for manual trace-overs by architects and BIMs. Architectural BIM software, such as Autodesk® Revit® and *Microstation*, without connection to software add-ins, rely on manual modeling processes over a point cloud background (reference). As an example, Figure 4.6 shows a 2D section of a PCM out of which Autodesk® Revit® elements are being created.

Figure 4.6- 2D plan view showing how a PCM (points in blue, red and green) is used as a template for constructing BIMs (straight black lines) in Autodesk® Revit®. Source: image courtesy ArcHC_3D

Figure 4.7 shows the same models (underlying PCM+BIMs) in a 3D view.

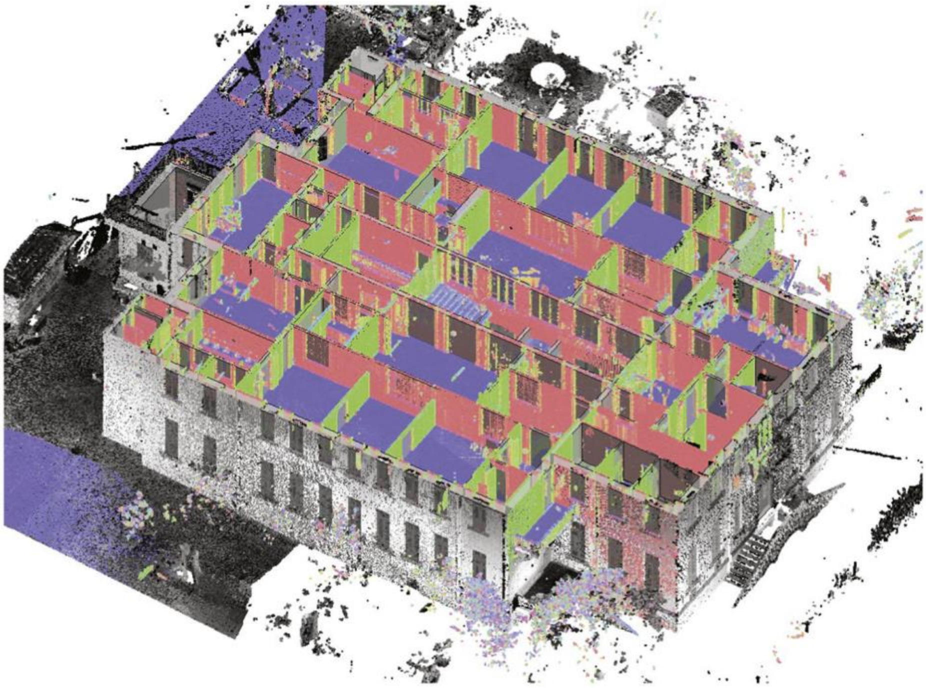


Figure 4.7- 3D view showing the 3D model resulting from tracing the PCM in Figure 4.6. Source: image courtesy ArcHC_3D

So, it is possible to visualize the point cloud in the application but there are no standard tools to semi-automatically or automatically recognize the point cloud properties and create a 3D solid model from it. As an example, in Arayici (2010) the 3D Data (mesh) is edited in the Polyworks IMEdit software module, in which cross-sections are created and exported to a CAD application, such as *Microstation Triforma*. These cross-sections are then used as templates for generating a new CAD model. In Chenaux et al. (2011), we can find case studies, such as the National Monument in Edinburgh, the Karolinum in Prague or Henrietta Street in Dublin. In these case studies, 3D data are again used, complemented with 2D data in some cases, as templates to draw 2D drawings in CAD platforms (*ArchiCad* and *Google Sketchup*), which are then again used to model a new 3D model. A number of automation initiatives can nevertheless be named, targeting at automatically creating a draft three dimensional model from a point cloud. These tools implement a reverse engineering approach in order to provide some level of automation at least. The idea is, in this case, that the CAD application (e.g. *Geomagic, Rapidform Xor,* and *3DReshaper*) recognizes the shape of a PCM or a NURBS model and automatically generates solid objects with distinct surfaces. However, this is in most cases done for the recognition of geometry only, and not for the recognition of semantically richer BIM objects, as one would require in rehabilitation and refurbishment projects. Only a limited number of automation initiatives aim at BIMs (including more semantically meaningful information) from a PCM. For example, *Scan to BIM* and *Edgewise Building* software have an automated recognition and placement of elements, including walls, columns, and pipes. *Kubit Virtusurv* for *Autodesk® Revit®* allows to semi-automatically recognize shapes in point clouds and connect them to *Autodesk® Revit®* elements.

To our knowledge, these tools are currently underused by rehabilitation and refurbishment specialists due to their costs and required level of expertise. They require a significant amount of user input, because of the complex geometry that is often present in existing buildings: walls are not exactly planar; corners are rarely orthogonal; elements can have deformations; and so forth. To make things even worse, the manually modeled objects will typically be used only once, as they most likely do not appear in any other building either. So, both directly and automatically recognizing BIM objects; and transforming surface models into volumetric models that include detailed geometrical and semantic information are subject of research rather than of realizations.

The challenge of combining traditional and unconventional survey techniques with BIM requirements and procedures is a second important element that is not commonly available in any of the existing BIM standards or guidelines, because this is a phase that typically does not exist in a stand-alone construction project. If a BIM standard or guideline would be devised for existing buildings and interventions in existing buildings, it could indicate the available survey techniques and outline through an explicit outline of exchange requirements and process model swimming lanes how the data coming from these surveys can be incorporated and effectively brought into the BIM modeling stage. Of course, a BIM guideline for existing buildings can only make note of recommended procedures. The actual implementation at project time depends on the agreements that are made between the project partners at the outset of the project, like many of the recommendations available in the existing BIM guidelines for traditional construction projects.

(3) Maintenance of information

In answer to the above two points (high modeling effort and uncertainty), it might be an option to try to maintain the information in BIMs from the moment when it is available (after construction, after the first intervention in the building that required BIMs) to the moment when it is needed again (and longer). This approach is the same as the BIM-FM-BIM scenario mentioned earlier. However, it appears to be complex and time-consuming to try to preserve the correspondence between the parametric model and the existing facility, because this is not typically understood as a core task of a facility manager. This is also considered as an important third barrier by Volk et al. (2014). The core task of a facility manager obviously is “managing the facility,” not “maintaining BIMs and leaving the facility on its own.” Because there is no real incentive for these facility managers to maintain the building information in BIMs that compensates the extra effort required from them, it simply does not happen. Even in the unlikely event that one is able to obtain a 3D information model for an existing building while still having the time to keep it up-to-date with occurring changes to the actual building, one still typically faces a lack of BIM modeling expertise. In case BIMs are available in Autodesk® Revit® or ArchiCAD, manually modeled from scratch or from a coarse point cloud, it is then handed over to the building owner (at best), who lacks the capacities to update the model with further changes.

4.6. BIM standards for existing buildings interventions

4.6.1 The need for BIM standards for existing buildings intervention planning

It can be concluded from the last section that there are an important number of hard challenges (three, to be precise) for which an efficient solution is not readily available in the short term. Many of these challenges resemble the challenges in a "regular" architectural design and construction project. Namely, complex and large data sets are also to be exchanged in such projects, which typically also require considerable amounts of manual modeling effort. A number of steps in the procedure can be automated, but other steps simply require human interpretation and thus manual modeling. Existing buildings differ from case to case and should thus to some extent be handled individually.

There have been huge efforts in the domain of "regular" architectural design and construction projects (the AEC domain) to address these challenges in this domain. As indicated in the beginning of this chapter, this has resulted not only in numerous BIM platforms and technologies, but also in national BIM standards and guidelines. BIM platforms and technologies have hereby helped a lot to improve basic information exchange in any collaborative architectural design and construction project, often resulting in a BIM Level 2 project collaboration (see Figure 4.2). The national BIM standards and guidelines bring this to yet another level (bringing BIM Level 3 project collaboration closer – Figure 1), because they allow to address and streamline precisely those qualitative features of collaboration (manual modeling, non-technological information exchange, agreements, quality control) that mere technologies cannot address. Following these conclusions, we suggest to build a set of national BIM standards and guidelines for existing buildings and for interventions in existing buildings as well. The main barriers to BIM adoption for modeling existing buildings and for devising interventions in these buildings, as they were outlined by Volk et al. (2014) and also recognized in our on-site work on this topic, are qualitative of kind for a large part. Technology will only help to improve information exchange to some extent. What would be a great support for the information exchange around existing buildings, are agreements, guidelines, and standards that indicate best practices and issues on handling the specific issues in this domain: (1) handling uncertain data coming from on-site surveys; (2) labor-intensive and error-prone modeling and conversion efforts in all forms of exchange; and (3) recommendations in terms of maintaining BIM information.

4.6.2. An appropriately guided combination of automatic and manual techniques

It is clear by now that, at the core, we propose to rely on a good combination of automatic and manual modeling tools. This is a delicate balance. For modeling existing buildings, a purely manual approach (left in Figure 4.8) is not appropriate, but neither is a purely automated approach (right in Figure 4.8). A good balance needs to be chosen, which allows for efficiency and qualitative interpretation. We believe that this can best be achieved through the combination of BIM approaches, which only bring you up to Level 2 BIM, extended with practical guidelines around exchange in the process. At best, this combination puts us on the verge toward Level 3 BIM collaboration.

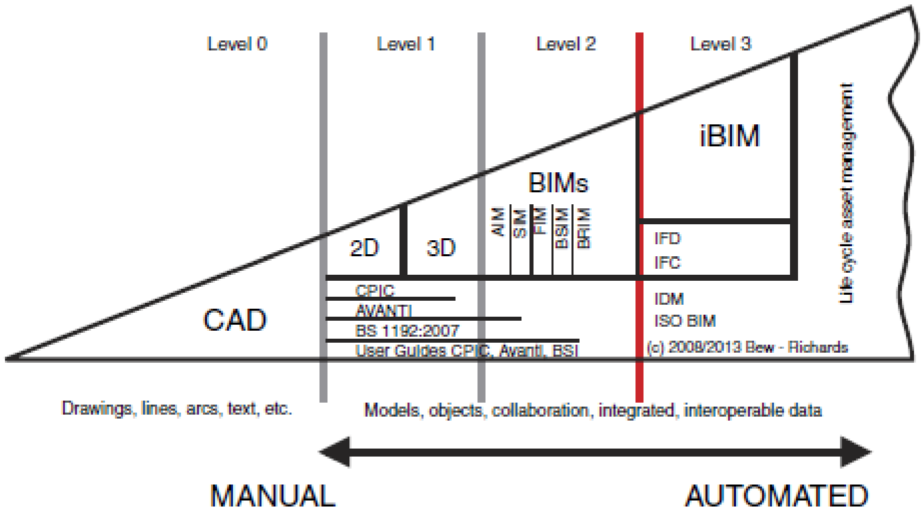


Figure 4.8- The spectrum of manual modeling and information exchange toward automated modeling and information exchange, overlaid over the BIM levels diagram displayed earlier in Figure 4.2. Source: Figure adapted from image by Bew and Richards, as

declared in BSI (2013) page vii

Further improvements may come forth from an agreed set of guidelines for (manually) modeling existing building objects. The BIM standards that are available in regular design and construction projects provide some steady ground that allows construction experts to develop a common understanding and agreement of what is supposed to be modeled and exchanged within one particular project at least. As a consequence, anyone that comes into contact with building information in such projects knows what he can expect and knows what he is supposed to deliver. We claim here that such a steady ground would also be useful in a context of existing buildings that require refurbishment and/or rehabilitation interventions. It would allow to perform manual modeling work in such a way that: the result of the manual modeling is of later use to other people; and that automatic tools can interact with and partially provide the results of this manual modeling work.

The use of BIM standards would thus streamline and further optimize the more pragmatic approaches (manual+automatic) that are currently in place for performing rehabilitation and refurbishment projects for existing buildings, as it currently also occurs in “regular” architectural design and construction practice. Through an agreed upon quality label, these guidelines could contribute to diminish the high modeling effort, the difficulties in handling uncertainties, and the struggle of maintaining the information up-to-date. It would be easier and more appealing for a building manager and building intervention planner if they had guidelines on BIM for existing buildings: what to model, how to develop the elements in the model, what information should the model contain, and how should information in the model be exchanged.

4.6.3 Application of BIM standards for intervention planning in existing buildings

It is possible to complement and adapt existing BIM standards for rehabilitation and refurbishment projects in existing buildings. There is a common logic between the BIM of new projects and of intervention projects in existing buildings. To apply the BIM standards for existing buildings, one has to establish this relation and understand what is similar and what is different. We have summarized this relation in Table 4.1, based on the above sections. In this table, we outline what traditional construction projects, and thus also their BIM guidelines and standards, focus on. In addition, we display what kinds of data set requirements, exchange requirements, and process model requirements are of central importance to any intervention in an existing building. These are the aspects that need to be incorporated in any forthcoming BIM standard for existing buildings (Table 4.1).

	Traditional construction projects	Interventions in existing buildings
Data formats	IFC, DWG, RVT, DGN	RVT, IFC, DGN PCM, TLS, ADP Historical BIM data/FM data
Exchange requirements	MVD Level of detail Level of development	MVD Level of detail Level of certainty Modeling tolerances
Process model	IDM, BPMN Design phase to construction phase	IDM, BPMN Survey phase to operational phase

Table 4.1- The different requirements for traditional projects and existing building projects

(1) Data modeling requirements

We assume here that no BIM is available at the outset of an intervention project in an existing building and a building survey is required. In this case, it is important that the data from the building survey is accurate, so that it is usable, and standardized, so that it can be included in a BIM environment. So, having standards that promote correspondence between survey data and a BIM environment would simplify the communication among involved stakeholders, and would better connect model and reality.

Information classification standards, such as OmniClass, IFC, and COBie, are not often used for representing existing buildings and related processes. The reluctance on the application of these standards can be due to the fact that they just partly enable deconstruction and recycling functionalities. They do not include pathology classifications, deformations, or levels of degradation. These standards neither have classification elements for specific construction elements that are no longer used nowadays. COBie has difficulty in framing and defining complex and specific elements regarding the field they belong. The answer to this lack could be to establish a link between the proposed guidelines for existing buildings and standards and guidelines of traditional methods. We could merge classification schemas of traditional element classifications in the new classification systems and adapt them. Standards regarding existing buildings classifications can be found in specifications documents like Metric Survey Specifications for Cultural Heritage (Bryan, 2009).

In addition to these standards that are at play in regular existing buildings (historical BIM data and FM data in Table I), BIM standards and guidelines for existing buildings additionally need to take into account the data formats that are at play during the building survey phase. As we indicated in our paper, there are a number of techniques used in this field that are seldom used in the regular architectural design and construction industry, such as the TLS and ADP survey techniques.

Agreements on how these data formats (PCM) can be used and ported into existing BIM software can notably improve building survey procedures and BIM adoption in this domain.

(2) Data exchange requirements.

Regarding data exchange requirements, it is important that BIM standards provide some guidance regarding the possibilities and recommendations regarding modeling tolerances. A modeling tolerance level indicates the level of interpretation and simplification of reality. Depending on the modeling interpretations made when modeling from a PCM, a particular indication can be added to indicate the modeling tolerance level. The chosen modeling tolerance should specify either a low, medium or high tolerance level, depending on the required output. This tolerance could be 60, 30, or 15 mm, for example. This means that, for example, the vertical and horizontal deviations of an object wall from the PCM points should not exceed the chosen tolerance values. The Plowman Craven BIM Survey Specification and Reference Guide document (Plowman Craven, 2017) is an example of such guidelines that could be used as a reference document. Once there are modeling tolerance guidelines, it will be easier to model and reuse elements.

Based on these modeling tolerance statements, data exchange can occur in a more trustworthy and reliable manner. For example, when modeling an existing building, a modeler has indications about the dimensions that are to be considered, so that he does not unnecessarily need to represent elements smaller than the specified modeling tolerance level; or so that he is able to consider the maximum deviation to be considered when modeling an object.

Besides considering modeling tolerances, data exchange requirements in BIM standards should also take into account the LOC for BIM objects. This LOC can be considered very similar to the LOD concept used in regular construction projects and associated with it. Being able to assign an adequate LOC for modeling existing building elements would be valuable to guide rehabilitation and/or refurbishment projects starting from these building elements. For an intervention in an existing building, a LOC 200 representation might in many cases be sufficient, indicating only a generic position for the model object and possibly element type information. The objects should be easily editable, having all the possible parametric variations included so that they can be used in a number of projects. From this LOC comment associated with LOD representation a reasonable transition can be made to the usage of LOD annotations for the new elements, which is part of existing BIM guidelines.

(3) Process modeling requirements

Also at a macro scale, BIM guidelines for existing buildings will differ from BIM guidelines for the "regular" architectural design and construction industry. Not only is there an additional process that needs to be taken into account, namely, the building survey phase, also the interactions with the information coming from this additional process need to be carefully considered in the downstream BIM processes aiming at a full intervention project in an existing building. How are the certainty levels (LOC) to be interpreted, can modeling tolerances be reconsidered at some stage, how to rely on point cloud data toward the end of the project.

4.7. Conclusion

We have seen in this chapter that BIM standards contribute to the creation of reliable and useful information, maximizing production through a coordinated and consistent approach, ensuring high-quality project deliveries and efficient data sharing and communication in multidisciplinary projects. In general, BIM standards contain data structure and identifier standards, exchange requirement standards, and process model standards. These elements allow to create a standardized understanding of what the information exchange really is, to specify which information to exchange and when to exchange the information, and to standardize formats for information exchange. These standards are typically defined and described for new building projects. The majority of intervention projects in existing buildings, however, are seldom modeled in a BIM environment, but are modeled using traditional methods instead.

Next in this chapter, we have looked into multiple potential benefits of using BIM environments for modeling existing buildings and intervention projects, in these existing buildings. These benefits are currently not covered by industry and are only sporadically mentioned in literature. Several challenges hampering BIM software adoption for planning interventions in existing buildings have been outlined previously. Namely, BIM software adoption is hampered: because of the required modeling/conversion effort from captured building data into semantic BIM objects; because of the difficulty in maintaining information in a BIM; and because of difficulties in handling uncertain data, objects, and relations occurring in existing buildings (Volk et al., 2014). There is thus no methodological recipe for managing existing building interventions.

From this analysis, we have made a case for devising BIM standards for modeling existing buildings and intervention projects in existing buildings, in order to remedy at least some of the manual effort that will in any case be required in modeling an existing building and the intervention project in this existing building. The proposed content for BIM guidelines includes modeling tolerances and adequate LOC descriptions for modeling existing building elements; and information standards for existing building interventions that link classification schemas of traditional element classifications with the new classification systems adapting them with pathologies classifications, deformations, or levels of degradation. This allows to diminish the high modeling effort, the difficulties in handling uncertainties, and the struggle of maintaining the information up-to-date, since stakeholders have a common understanding and agreement of what is supposed to be modeled and exchanged. It also allows the production of modeling outputs that are of later use to other people, and automatic tools use that can interact with and partially provide the results of these outputs. As a result, intervention projects in existing buildings will happen more efficiently.

5
As-built BIM workflows

Based on the as-built BIM adoption problems previously identified and outlined by Volk et al. (2014), and described in chapter 4, this chapter describes case studies from which workflows or guidelines can be extracted for: (1) the handling and modeling of uncertain data, objects and relations occurring in existing buildings in BIM; and (2) the high modeling/conversion effort from captured building data into semantic BIM objects. Regarding the difficulty in maintaining BIM (3), this chapter outlines as-built monitoring data analysis as a first step for maintenance of information in BIM.

In this chapter, several as-built BIM workflows are presented. There is not one answer on how to address as-built BIM data and workflows: every case is specific and different. The intervention approach is different according to complexity, scale and use of the object; it varies with the intervenients and their skills, which are correlated with software knowledge and general experience. The goal of this workflows research is to produce and receive information in a consistent data format, resulting in a more efficient information exchange and compatibility between projects.

The development of this research was made majorly focusing on existing building intervention refurbishment projects. This choice is justified by our belief that this kind of projects can be improved using BIM. The as-built BIM workflows are developed through the analysis of individual cases, resulting from three years of research experience at three architectural companies (Dark Arkitekter, Beck Group, Grape Architects) additional to the two years research with the ArcHC_3D research group of FA-ULisboa. In each project we will go through key problems and solutions.

Autodesk® Revit® was used in the development of the projects discussed in the case studies of the present thesis. This choice is due to several reasons: performance, licenses and its use in the companies where research was developed. In 2012, when I started the research of point clouds use in BIM, Autodesk® Revit® was the software I had access to (due to student license) and that indexed point clouds in an easier way and where visualization performance was faster when orbiting the point cloud. This was concluded after comparing point clouds insertion and visualization, in *Autodesk® Revit®* and *Archicad*. The second reason is the use of this software in the three companies where the research was developed. Nevertheless, it is important to outline that this thesis does not intend to focus on software tools, and the end result guidelines and conclusions are transversal to all platforms.

In this research a three-month PhD internship was done at Dark Arkitekter, an architectural office in Oslo, Norway. The internship goal was to understand how and if point clouds were used in the existing building projects interventions, as well as how their use could be improved. Following that, the research continued as full-time work, first at Dark Arkitekter, then at The Beck Group and after at Grape Architects.

A short description of the companies will be addressed, to understand their main characteristics and consequent resources and workflows. Dark Arkitekter is an architectural company, with approximately sixty employees, focused on architectural projects. The Beck group is a five hundred employees company with construction and architectural units. The described case studies from this company were developed inside the VBG (Virtual Building Group). This group performed the 3D surveys and BIMs internally for the architects and for external companies. Grape architects is a 12 employee company working with architectural projects

In the next sections we will focus on analyzing the as-built projects:
From ArcHC_3D research group at FA-ULisboa:

- ❑ Belem Palace survey (2011)

From Dark Arkitekters:

- ❑ Ruseløkkveien project (2015)
- ❑ Akersgata project (2015)
- ❑ Karl Johans Gate 8-10 project (2015)

From The Beck Group:

- ❑ El Jebel project (2016)
- ❑ Medica Sur project (2016)
- ❑ College Station Theater project (2016)
- ❑ Trinity forest survey (2016)

From Grape Architects:

- ❑ Briskebyveien 38 project (2017)

- ❑ Sognsveien project (2017)
- ❑ Vitusapotek Volvat study (2017)

The first observation that can be made is that each company used a combination of different software tools that were interoperable between each other, but *Autodesk® Revit®* software was used by all companies. It is important that the same software is used within the same company. This is due to high software prices (licences according to number of users); training, since it will be more expensive to have training for different software that does the same in the end; standardized methods and knowledge, as it is difficult to specialize in different software with the same results. Summarizing, it is important that a company has software consistency. It is fundamental that consistency, standards, and definition of goals are taught and applied in the beginning of a project.

The next sections are project studies that intend to create guidelines and are grouped according to the issue they are studying. It was analyzed the acquisition of data and the modeling process. The modeling research was subdivided in analyzing final BIMs elements and modeling workflows. Figure 5.1 illustrates the way in which Sections are divided and which topics are addressed.

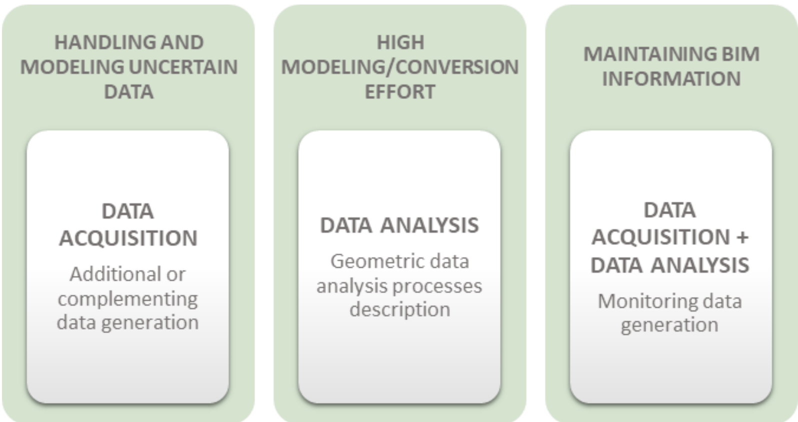


Figure 5.1 - Schematic diagram of the Section 5.1, 5.2 and 5.3 subjects

Section 5.1 addresses the issue of handling uncertain data, objects and relations, for modeling, by focusing on acquisition processes for additional or complementing data generation. Section 5.2 addresses the high modeling/conversion effort issue by describing geometric data analysis processes. Following this, Section 5.3. focuses on creating data for maintaining BIM information, specifically building monitoring data. Section 5.4. is the resulting analysis of the case studies and the comparison providing guidelines for the standardization of modeling workflows and data exchange workflows.

5.1. Handling uncertain data, objects and relations

To handle uncertain data and unclear or hidden semantic information (see Section 4.5.2), one can try to understand it by complementing the original data with additional missing information. This section focuses on different processes to create additional missing information, used to complement or as a base for decision making when no data is available (illustrated in Figure 5.2).

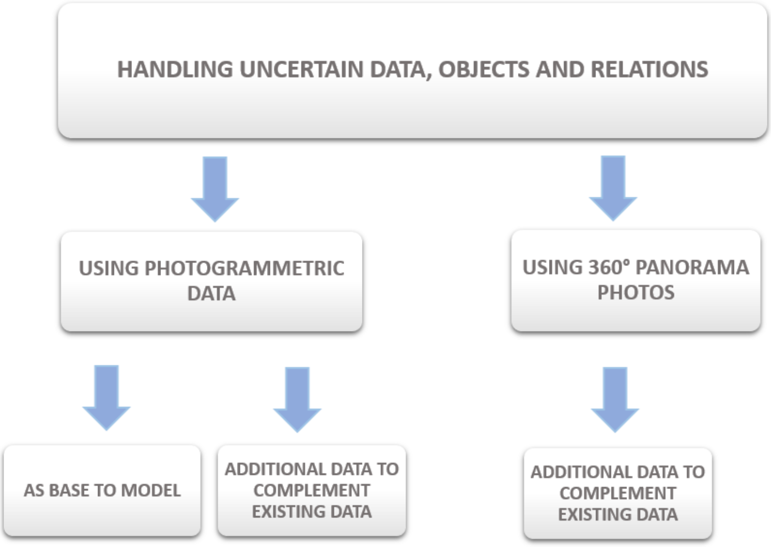


Figure 5.2 - Schematic diagram of the Section 5.1 subject sequence

Different kinds of information can be used, like photos, additional point cloud data, CAD drawings and/or hand drawings, among others. The workflows present in the following Sections address mainly the missing visible information, the hidden information will be referred to some extent but needs to be handled with different processes, pointed out for future work.

5.1.1. Using Photogrammetric data

Up to now, the most used survey technique in existing building intervention processes is TLS. Point cloud surveys can be done with different parameters that influence the final PCM; these are the number of scans, point density, range, resolution, precision, and color. Depending on them, the survey can take more or less time and consequently differ in price. The TLS survey captured in a medium point density and without color is usually enough for the extraction of the general shape of the building. Also, it is less expensive. But if the building is too complex, if the environmental conditions are not the best, or if the purpose of the survey is not properly established, the information generated will most likely be insufficient for the intervention project. Hence, there can be some areas that need more information after the survey is done.

TLS is expensive, so it is not always an option to do more surveys in order to add information. Furthermore, if the architectural office is dependent on the survey company's schedules and availability, it can increase delays on the project and consequently induce extra costs. TLS surveys are not the only option, ADP can be a low cost process, if done by offices as a complement of the first TLS survey, capturing absent information or complementing the existing information. The use of photogrammetry in the capture of buildings has a different workflow when comparing with the capture of smaller objects.

A. Photogrammetric data to complement existing data

Ruseløkkveien project |Oslo, Norway| Dark Arkitekter

Project goal:

This project had several building interventions planned, but this study focuses on the refurbishment of a facade and adjacent shops marked by rectangle A in Figure 5.3 and, in one of the facades to be intervened, marked by rectangle B in Figure 5.3.

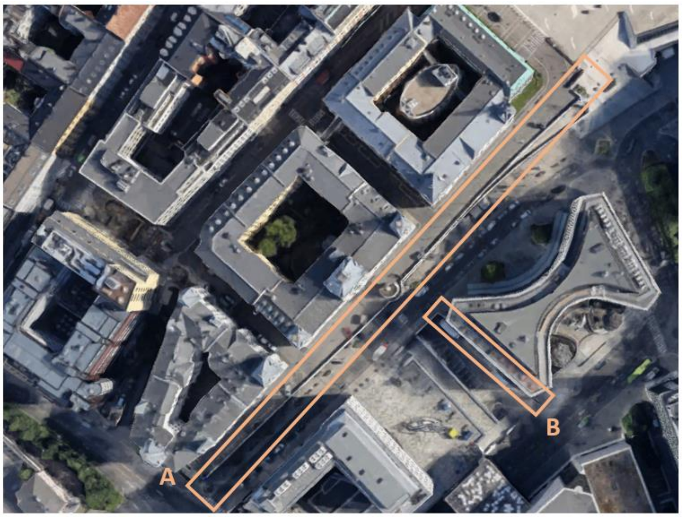


Figure 5.3 - Photogrammetric survey facades location. Source: Image courtesy Google maps

It was important to record the facades. During the project development through CAD drawings, there were some issues with missing information and conflicts of information. Additionally, the team needed to check the facade stone pavement heights. To solve this issue, a survey company was hired to execute a TLS survey of the area associated with the corresponding survey control network. There was some miscommunication between project and survey teams and the purpose of the survey was not understood. As a result, element dimensions and material colors were missing, restraining the team to model the facades. Although the facades have a repetitive pattern, the elements vary in size and thickness; and the inexistence of points leads the team to make assumptions and consequently create inaccurate results.

An additional ADP survey was done to capture the missing information (element dimensions) for two specific facades. The first survey was the shop's facade (Figure 5.4), which was a two level high stone and glass facade, very repetitive and long (approximately 180m).

Figure 5.4- Ruseløkkveien shops facade. Source: Google maps

The second survey was the facade shown in Figure 5.5 (signed by rectangle B in Figure 5.3), which was a nine level high concrete and glass facade, also with a very repetitive pattern.

Figure 5.5- Ruseløkkveien facade. Source: Google maps

Both facades were surveyed with a similar workflow and the outputs presented the same characteristics. For this reason, only one facade survey is represented in this case study. The next paragraphs describe the workflow used for the acquisition and processing of the facade marked by the rectangle B (Fig. 5.3).

Acquiring and processing workflows:

a. TLS survey

The TLS survey was done by an external laser scanning company with a Leica scanner associated with control survey and the data was registered in *Leica Geosystems Cyclone*. The computer capacity used was an Intel Core i7 4700MQ @2.4 GHz with 24 GB ram. The operating system was a 64-bit windows 7.

The project team required a point cloud survey with no color, no specification of density, no description on how it should be segmented, what formats should be delivered or an IDM registering what was asked and what was done.

Issues

The architects were having difficulties in understanding the point cloud data. The point cloud files had unwanted information like cars, people and scaffolding, which, in this specific PCM, should have been removed before, since this unwanted information hinders visualization and interpretation of the points corresponding to the building. These point clouds did not provide enough information to the repetitive facade pattern dimensional variation. The inexistence of points, representing these elements, lead to information assumptions and consequently to inaccurate results. There was also a need to understand material colors, so it was decided to execute an additional photogrammetric survey of the facade.

b. ADP survey:

The photo acquisition was done by Margarida Barbosa, with a handheld camera: a Nikon D750 with 24.3Mp camera. Figure 5.6 shows the schematic diagram of the acquisition and processing workflows and the case study steps sequence, described in the next paragraphs.

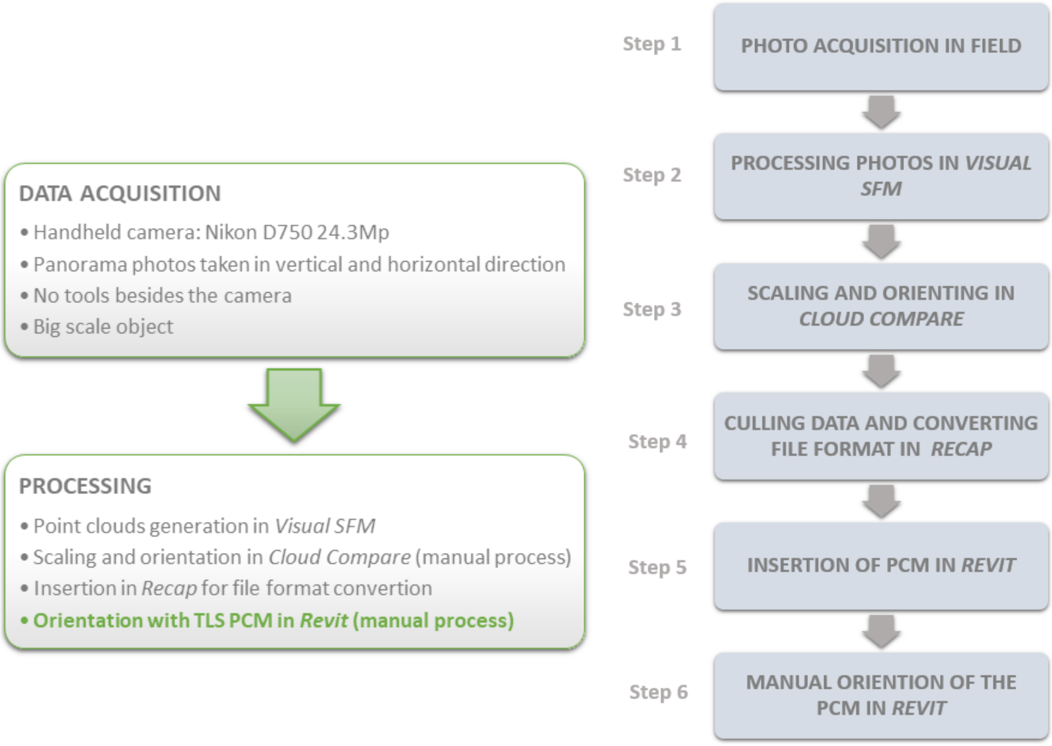


Figure 5.6- Schematic diagram of the acquisition and processing workflows and the case study steps sequence

One panoramic photo was taken every two steps with horizontal and vertical direction, to cover the building height and include all elements. During photo acquisition, the following guidelines were used:

- sensitivity of the image sensor: ISO 100
- capture photos every 5 degrees (two steps)
- overlapping photos without changing settings between photos
- no dark and no overexposed surfaces
- homogeneous lighting

The photos were processed in VisualSFM software. The sparse reconstruction (first sparse point clouds generated) took one morning and the dense reconstruction (final dense point cloud) approximately one day. The computer characteristics were CPU Dual intel® Xeon E3-1270 V2 3.50 GHz; 32 GB RAM, NVIDIA GeForce GTX970.

The resulting PCM had a lot of noise; the facades were difficult to interpret, as shown in Figure 5.7.

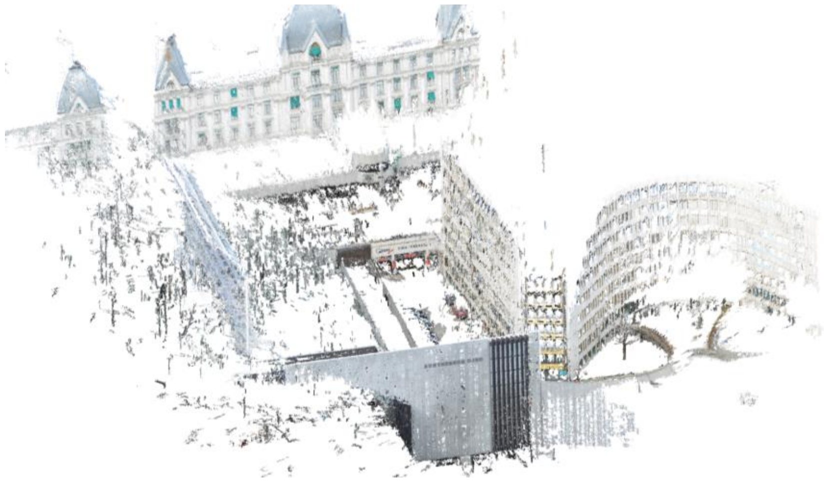


Figure 5.7- Photogrammetric PCM obtained through *Visual SFM.*

The PCM resulting from MVS for 3D generation has an arbitrary scale, orientation and position, as shown in Figure 5.8. We can understand the ADP PCM is the colored PCM on the left (A), while the TLS PCM is colored by the points normals (B) and has a correct scale, orientation and position.

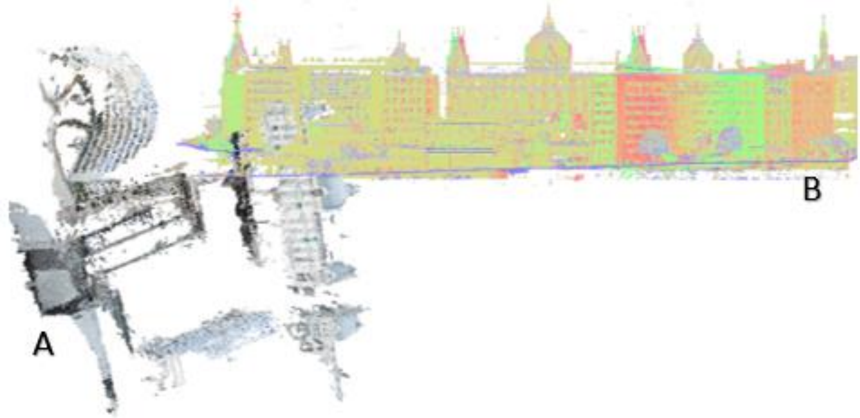


Figure 5.8 - Photogrammetric PCM has an incorrect scale and orientation

The PCM file was duplicated and imported into *CloudCompare,* where a y transformation and rotation were applied until the model was correctly oriented with the correct xyz reference.

To correct the scale, the same element in the TLS point cloud in *Autodesk® Revit®* and in the cloud compare was measured. The quotient between the *Autodesk® Revit®* measure and the cloudcompare is the scale that should be specified when importing the .txt from cloudcompare into Autodesk® Recap®. This will scale the entire model so it can be inserted in *Autodesk® Revit®*.

PCM extra noise that we observe in Figure 5.9 was cleaned in *Autodesk® Recap®* and the final cleaned PCM was imported into *Autodesk® Revit®.*

Figure 5.9 - Photogrammetric PCM noise: there are points that are not correct information and should be erased

The ADP PCM was manually positioned in Autodesk® Revit® by aligning a common element between the ADP PCM with the TLS PCM (Figure 5.10).

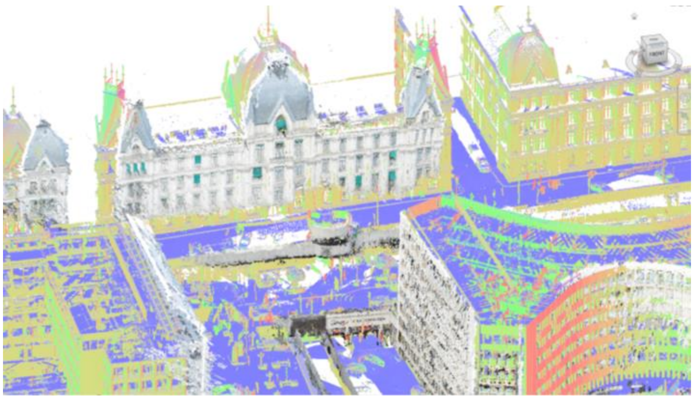


Figure 5.10- PCM positioned accordingly to the TLS point clouds

This alignment could be done in a more automated way if the coordinates of the common points between the two PCM were acquired in the TLS PCM and, the coordinate values were inserted into the ADP PCM points in *CloudCompare.*

<u>Critical analysis of workflow and outputs</u>

The acquisition with panoramic photos was not a good decision since the software used to process the photos prefers convergent points of view (instead of the divergent points of view of a traditional panoramic shot). Panoramic photos were chosen in an attempt to capture more data in one single shot, but it should not have been done since it does not generate outputs with enough quality. The resulting low quality PCM, from panoramic photos, can be observed in Figure 5.11. Also when one captures panoramic photos, the panorama adapters should be adjusted to ensure the alignment of the rotation axis and the perspective centre of the camera. This was not done in this survey contributing to the low quality PCM obtained. The final product would have improved if 45 degree angle photos and photos including floor were taken.

In some facades, the capture was really difficult due to car movements and because of the position between the camera and the facade, which also contributed to not capturing the floor. Regardless of the way in which they were captured, these facades were difficult to capture due to repeating patterns, strong shadows, lack of texture and highly reflective surfaces. All the described features introduce problems in the MVS PCM generation process. The part of the facade that is higher than 3 storeys could have been better captured if the camera was attached to an extension pole, to increase photos height and better convergent angles in the vertical axis.

Even after cleaning, there was too much noise on the point cloud obtained through photogrammetry; it was difficult to understand the facade and its information as we observe in Figure 5.11.

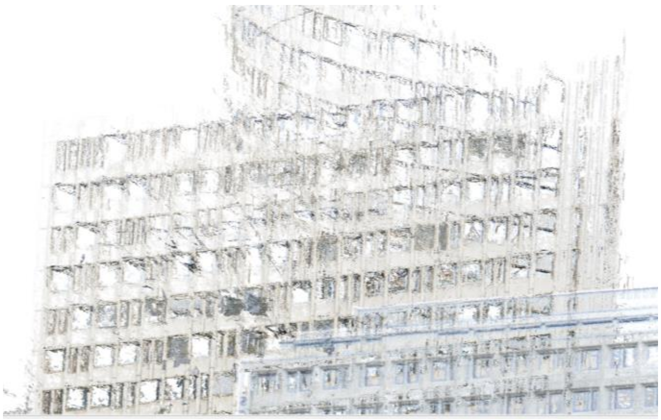


Figure 5.11 - Facade difficult to understand

When comparing ADP point clouds and TLS point clouds, there is inconsistency in the scale (Figure 5.12): some objects match but others do not. This indicates that more than one object should be measured and the average scale value obtained should be applied. It can also be a consequence of the data acquisition and processing inconsistencies, since all photos were acquired using low angles.

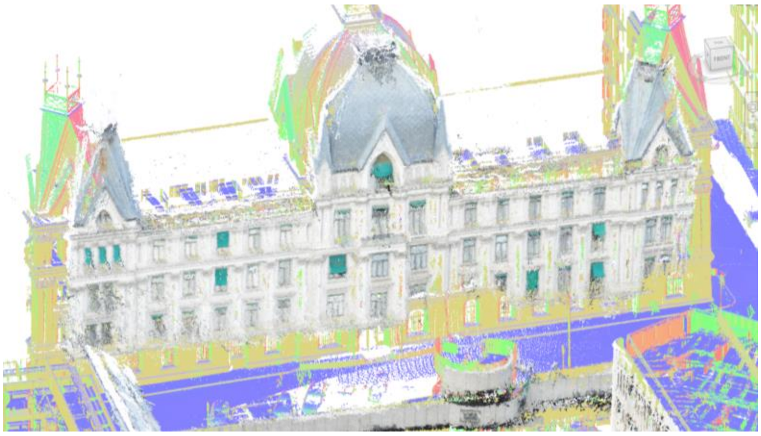


Figure 5.12- Comparing ADP PCM with TLS PCM

It was not possible to repeat the survey due to time limitations. Hence, the project team used the ADP PCM and the photos acquired for visual validations during the project development.

The handheld ADP survey difficulties lead me to the following assumptions:

- The survey should be planned earlier: according to its purpose, to acquisition strategy, where it is included, which photo capture technique is used (how to take the photos, how many, in which angle), the hour of day (the hours with less shadows on the facade in study), and the possibility of accessing neighbor roofs to capture higher viewpoints.
- The area of interest (in this case the building facade), when it has a big scale, should be segmented and captured in different surveys, to simplify the capture and processing work.
- The tools chosen for the survey should be tested and planned before, using tools like a handheld camera for smaller objects, and camera with extension pole or drones for bigger buildings, for example.

The acquisition process setup and process standards are important to allow generating data that is reliable and useful. The complementing data can be useless if one does not know the project intent. In this case, the accuracy of data is essential. The quality of the inputs control the quality of outputs. This case study shows the importance of having complementing data suitable for the project needs, resulting from a consistent and structured survey.

Briskebyveien 38 |Oslo, Norway| Grape Architects

Project goal:

This project was a store refurbishment, the goal was to preserve what already existed since it had been renovated recently. The base information, used for the project design, were CAD drawings. Nevertheless additional information, including general dimensions and dimensional information of the entrance stairs, was needed to understand if it was possible to create a ramp for universal design. Figure 5.13 shows the store facade and entry staircase that needed to be intervened.

Figure 5.13 - Store facade and entry staircase. Source: Google maps.

Acquiring and processing workflows:

Figure 5.14 shows the schematic diagram of the acquisition and processing workflows and the case study steps sequence, described in the next paragraphs.

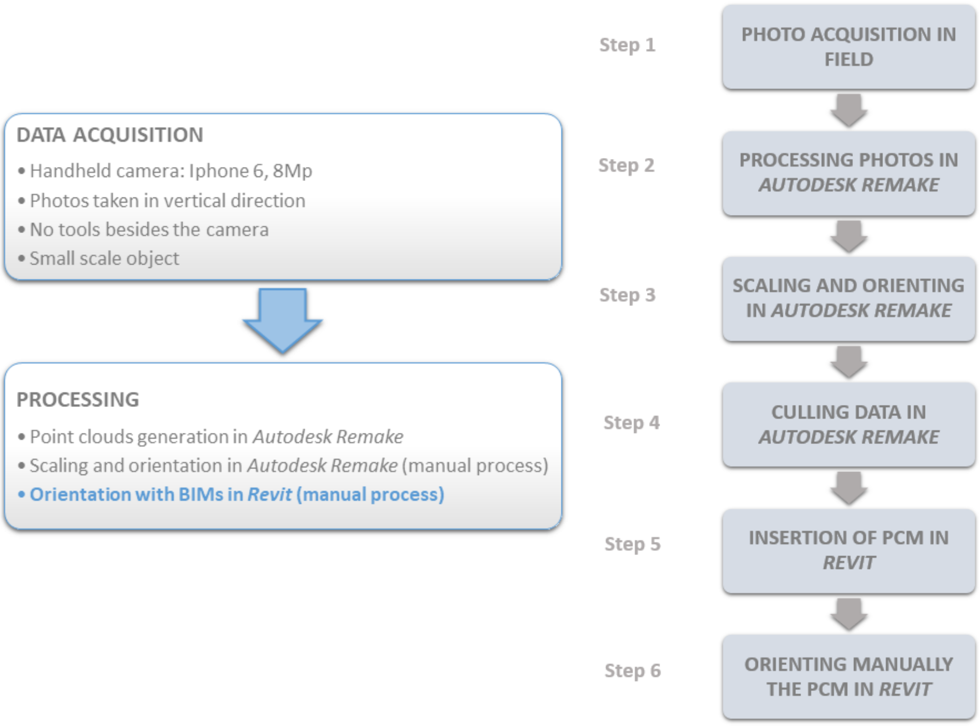


Figure 5.14- Schematic diagram of the acquisition and processing workflows and the case study steps sequence

ADP survey:

The measurements were taken with a laser distance measurer (Leica disto) and the outside steps were surveyed with 20 photos (Figure 5.15) taken with an iPhone 6 smartphone.

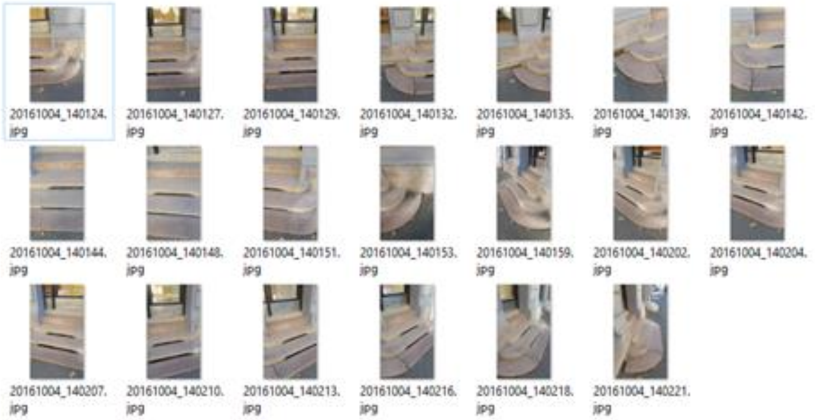


Figure 5.15 - Photos of the staircase taken with an iphone 6.

The photos were inserted in *Autodesk® Remake®*, and a point cloud was generated and scaled according to measurements taken on site, with the disto (Figure 5.16).

Figure 5.16 - Scaled point cloud of the staircase.

The next step was to integrate the point cloud data with the BIMs in Autodesk® Revit®. This was done by manually rotating and positioning the point cloud within the BIMs.

Modeling workflow:

The steps were modeled inside *Autodesk® Revit®* based on the point cloud information. A non-parametric stair element was generated due to time limitations, complex object shape and also to the fact that this specific element was not going to be edited. Figure 5.17 shows the point cloud and stair element obtained from it in *Autodesk® Revit®.*

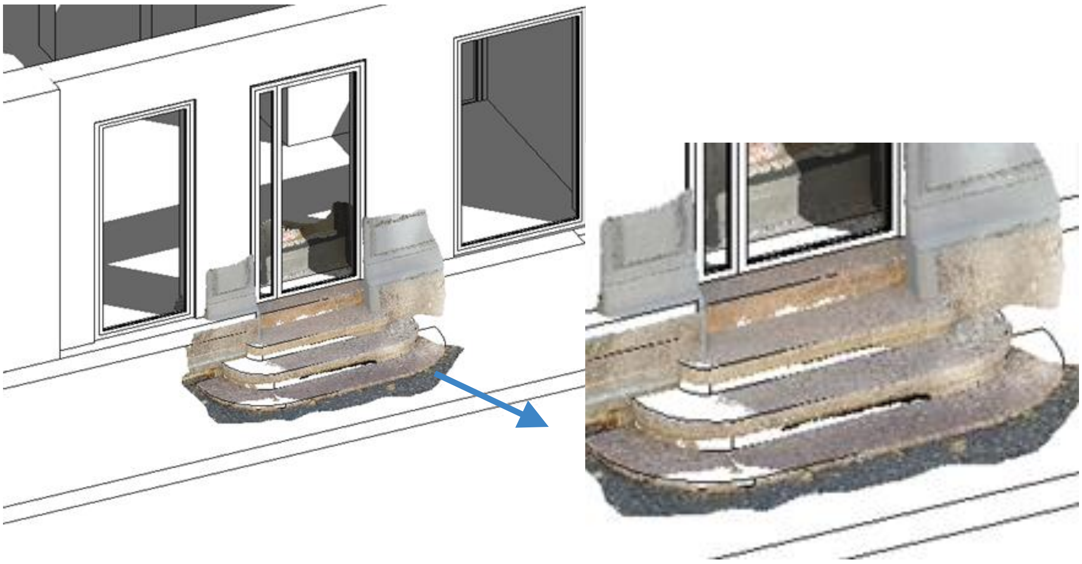


Figure 5.17 - Scaled point cloud and stair element obtained from it in the BIMs

The stair element was modeled within 5 millimeters from the point cloud. The dimensional measures were adjusted to the nearest 5 millimeters increments, with even values.

Critical analysis of workflow and outputs

The BIMs complemented with the point cloud allow to study different solutions for generating a ramp integrated with the steps and to understand how much space is left on the walkside. This is an example of how low cost handheld camera photogrammetry can be used in a reliable way to complement missing information in architectural projects.

Belém Palace survey | Lisbon, Portugal | ArcHC_3D

Project goal:

The survey goal was to document the exterior of the Belém palace (Figure 5.18) since it is a monument of national interest. The TLS survey was chosen for the facades survey but still there would be a lack of information regarding the roofs and other elements out of reach. This is why aerial photogrammetry was chosen to complement the main data. The survey team members were Luís Mateus, Victor Ferreira, and Margarida Barbosa.

Figure 5.18 - Belém palace exterior PCM

Acquiring and processing workflows:

Figure 5.19 shows the schematic diagram of the acquisition and processing workflows and the case study steps sequence, described in the next paragraphs.

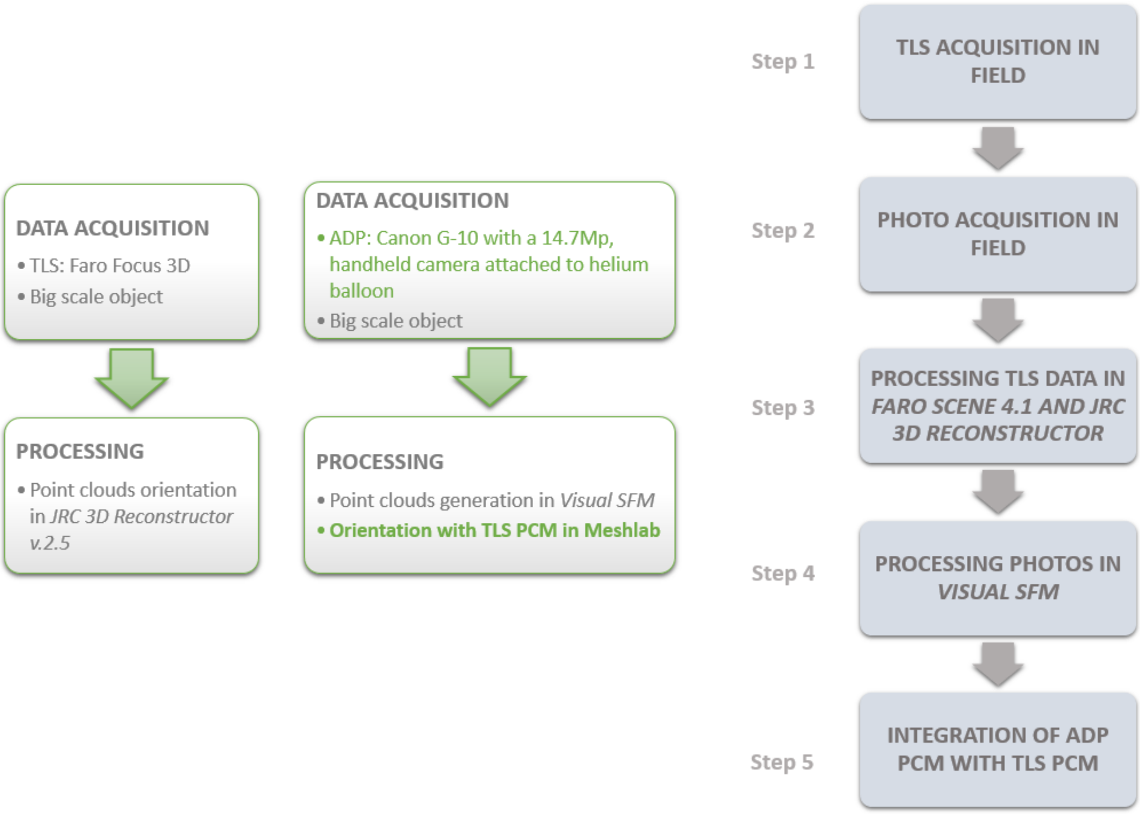


Figure 5.19- Schematic diagram of the acquisition and processing workflows and the case study steps sequence

The Belém palace exterior survey was done using a Faro Focus3d for TLS and aerial imagery collected with a Canon G-10 with a 14.7Mp, placed in a remote controlled helium balloon with $9m^3$ and a load capacity of 1.5Kg (Figure 5.20). TLS was used to capture the facades and ground while ADP captured the roof and data not accessible from the ground.

Figure 5.20 - Helium balloon being hold by Victor Ferreira (human scale).

The TLS data file format was converted into .ptx format in Faro Scene 4.1. Afterwards it was imported and processed in *JRC3D Reconstructor* software. Unwanted data, like reflection and refraction data, as well as people and cars, were removed. The final PCM was decimated through *JRC3D Reconstructor* and *Meshlab,* to reduce the file size.

The ADP data was generated through *VisualSFM* software and integrated with TLS PCM in *MeshLab*. They were used to complement each other, and ADP accuracy was obtained through the TLS one. This means the ADP point clouds were oriented and scaled according to the TLS PCM. We can observe in Figure 5.21 the integrated PCM resulting from TLS and ADP surveys.

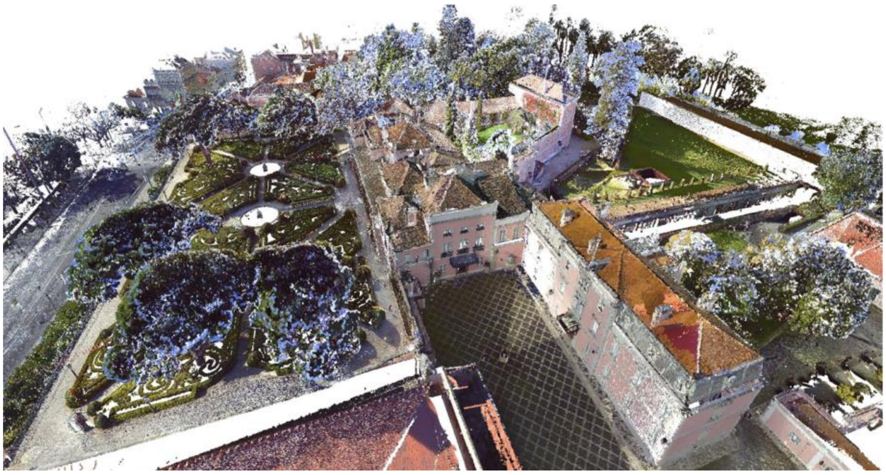


Figure 5.21- Belém Palace exterior survey: PCM resulting from TLS and ADP surveys integration.

Critical analysis of workflow and outputs

The TLS survey was used to set the overall geometry, and the aerial ADP survey was used to capture the roofs and elements out of scanner reach. The integration of these two processes combined their strengths, producing a final PCM with more complete information. The amount of uncertain or missing information decreases when these tools are combined. No BIMs were built from this PCM, nonetheless this case study is presented here as it outlines the advantages of starting with a planned, complete survey. If one was to produce a BIMs, it would be important to combine the planning of these surveys with the knowledge of the modeling purpose.

B. Photogrammetric data as a basis to start design studies

When starting a project, it is important to understand how the surroundings and the building or additions in the building relate. Photogrammetry can be used to complement previous existing information or as the basis for the project site study. This can be done in different phases of the project, with different levels of accuracy. In the conceptual part of the project or in the development of a project case study to convince a client to buy a building and refurbish/rehabilitate it, one can create a photogrammetric model through a 3D map like Google maps. The output data will have low accuracy, but the information is not always needed at the highest levels of accuracy. Depending on the purpose, low accuracy and low cost processes can also be valid. When the project starts developing and more accuracy is needed, aerial photogrammetry through drones, for example, can be used. If ground control points are associated to this GPS photogrammetric survey, the accuracy increases. The level of accuracy and the information that needs to be delivered vary from project to project and between project development phases, according to the purpose/goal.

Trinity forest | Dallas, TX| The Beck Group

Project goal:

This project was a new golf course, clubhouse, and support facilities in the Trinity Forest in Dallas (Figure 5.22). To develop the project, the team needed to understand the complex site terrain conditions. It was decided to compare site data resultant from aerial (through drone) survey, TLS survey and existing topographic CAD drawings. This study was done to understand the best process for future site acquisitions. Although this is a project for new buildings, the process of capturing and analysing the terrain can be applied to existing building interventions when the project includes terrain interventions. The TLS survey team members were Micah Gray an Margarida Barbosa, the Aerial ADP survey was done by Grant Hagen.

Figure 5.22 - Trinity forest golf camp site. Source: Google maps.

Acquiring and processing workflows:

Figure 5.23 shows the schematic diagram of the acquisition and processing workflows and the case study steps sequence, described in the next paragraphs.

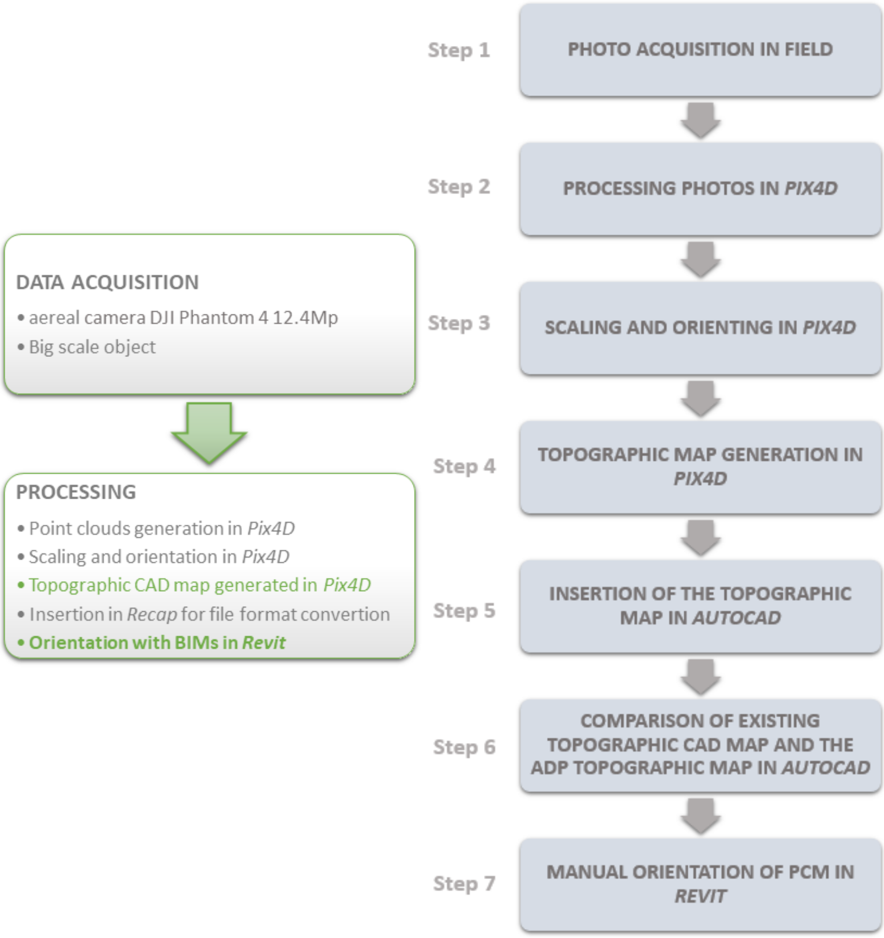


Figure 5.23- Schematic diagram of the acquisition and processing workflows and the case study steps sequence

In this project, the team compared a site acquisition with TLS and ADP, observed in Figure 5.24. We can see the same site took 2 days to acquire with a Leica scanner P30 and 3 hours in ADP survey with a DJI Phantom 4 drone. This time refers only to the acquisition part, not to the processing time.

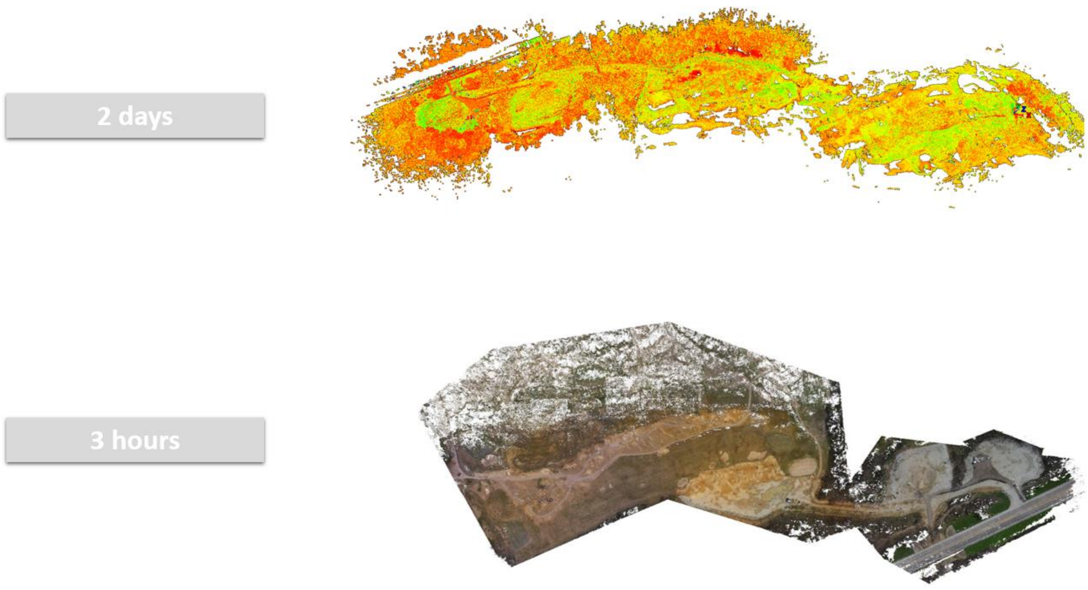


Figure 5.24 - Comparison of a site capture with ADP and TLS

The ADP drone survey is faster than the TLS survey in big scale outdoor conditions, considering it is faster to remotely fly a tool than a person transporting a heavy tool throughout several positions. The difference of hours is also justified by the site scale and difficult conditions, where it was challenging to relocate the scanner through the mud and to properly setup the targets and control points.

The processing time of TLS data was 2 days and was done through *Leica Cyclone* software. The processing time for ADP data (1718 photos) was around 1 day and a half, to produce the PCM, a mesh and contour line map (Table 5.1). The software used was *Pix4D*.

	Number of Images	Point Density	Time for Initial Processing	Time for Point Cloud Densification	Time for Contour Lines Generation	Total Time	
Trinity Forest Aerial capture less density	1718 out of 1750 images calibrated (98%), 24 images disabled	Optimal	27h:31m:11s	09h:49m:54s	05m:30s	38h30m	1 day and half

Table 5.1 - ADP processing time

<u>Critical analysis of workflow and outputs</u>

The ADP processing time varies according to settings, like point density and outputs desired, and the drone flight path. In this case the flight path was not structured and was trying to cover the most terrain possible, as can be observed on the left image of Figure 5.25. On the right, we can see an example of a structured flight path which was found to reduce the computation time.

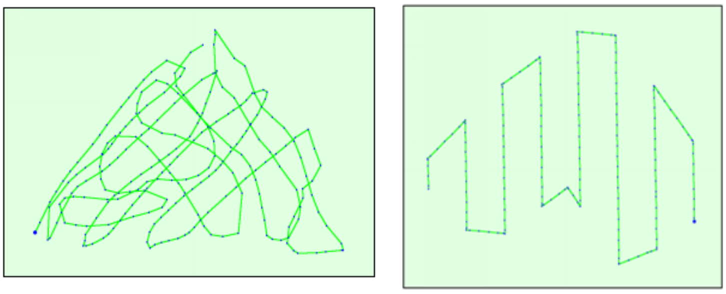


Figure 5.25 -Drone flight path pattern examples: unstructured on the left, structured on the right.

In Table 5.2 we observe the processing of a smaller site in terms of area (around half size) compared to Trinity forest site.

Number of Images	Point Density	Time for Initial Processing	Time for Point Cloud Densification	Total Time
539 images calibrated	Optimal	1h:30m	00h:30m	2h00m

Table 5.2 - Example of processing time with acquisition done through a structured flight pattern

The total time of processing was 2h for 539 photos. The flight path was structured, as we can observe in Figure 5.26.

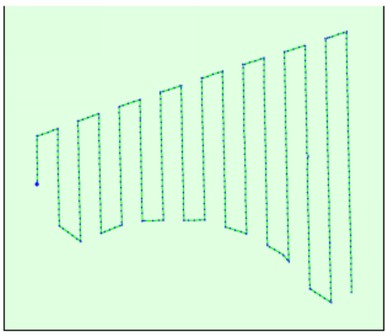


Figure 5.26 - structured drone flight path pattern

If the same kind of flight path, acquiring and processing settings were applied to Trinity Forest project, one can infer that it would take around 6,4 hours of processing for 1718 photos.

One can conclude that aerial ADP through drones is a fast way of surveying site data. From the aerial ADP PCM, one can obtain a contour line topographic map. Figure 5.27 shows a topographic CAD map, generated through Pix4D. The scale of the model was based on the drone GPS.

Figure 5.27 - topographic CAD map generated through Pix4D.

Figure 5.28 compares the generated CAD map, in red colors, with the traditional map, in green colors. We can observe that, although the map obtained through photogrammetry is not as simple and clean as the traditional one, there is a high equivalence between data.

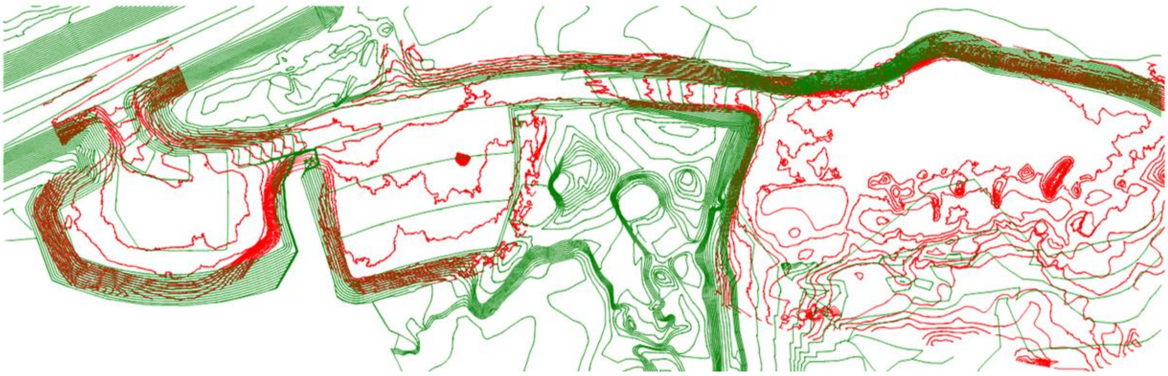


Figure 5.28 - Comparison of the CAD map generated through photogrammetry with the traditional CAD map

This kind of studies can be used to compare differences in earth volume movements, when moving soil on projects. For this goal, the data obtained through the aerial ADP has an accuracy within the acceptable limits. If the purpose of the survey requires more accurate data, one can increase the accuracy of an aerial ADP survey by associating its output data with Ground Control Points (GCPs). GCPs (Figure 5.29) are points of known coordinates in a specific area, which are acquired with traditional surveying methods like total stations. GCPs must be easily visible in aerial imagery, so they are usually large targets marked on the floor with high-contrast colors. Figure 5.25 shows an example of GCP captured by drone imagery.

Figure 5.29- GCP captured by drone imagery. Source: image courtesy Google

GCPs are required if there is need for georeferenced outputs. In this case, the GCPs will scale, orient and position the final results. Additionally, they are very useful for increasing the PCM relative accuracy. The landpoint surveying company used GCPs on an 85-acre map to obtain an accurate aerial survey, saving over 80 man hours compared to traditional land survey methods.[32]

The process consists in adding the GCP points to the processing software, for example Pix4D, and manually picking the marks and identifying which GCP the user is picking, in several images. This will correlate the points obtained through the photos with the accurate ground points (obtained with a total station for example). This workflow is used for advanced project phases, like the construction phase, that need really accurate data to start the intervention.

Until now, the majority of offices used CAD topographic maps. They are used for georeferencing sites and including the terrain in the 3D model. When their coordinates are inserted in the BIMs, it is possible to insert several different models into the same origin and position as long as they share the same coordinate system. Hence, the site survey can be done by architectural offices through aerial photogrammetry, usually outside cities due to security regulations. Aerial data acquired by drones associated with control survey, can be used to replace these CAD maps. It is an easy and cheaper way of having visual data of a specific project site. In Figure 5.30, we observe the Trinity Forest project that uses the photogrammetric PCM to illustrate how the project relates to the site.

[32] https://blog.dronedeploy.com/what-are-ground-control-points-gcps-and-how-do-i-use-them-4f4c3771fd0b

Figure 5.30- Aerial photogrammetric PCM used for site connection with design options. Trinity forest

This case study demonstrates how an architectural office could acquire up to date and accurate data, in a short period of time and with small investment. This is relevant when site information is missing or to develop site analysis like the ones described in Section 2.4.1 in Figure 2.22.

Vitusapotek Volvat study

Case Study goal:

Not always is the most accurate data necessary. For several initial projects or for buildings that an office wants to convince clients to invest in, low accuracy, cheap and quickly obtained data will suit the purpose. This type of data can be useful, for example, when starting studies of volume addition in a site where there are other buildings and one wants to understand how a new volume would change the area or to demonstrate that possible additions would be inside the site's regulation for heights. This can be done by generating a point cloud of the area being studied, adding it to Autodesk® Revit® software and generating mass volumes to see how they relate. Figure 5.31 demonstrates the logic of adding a new volume to an existing one.

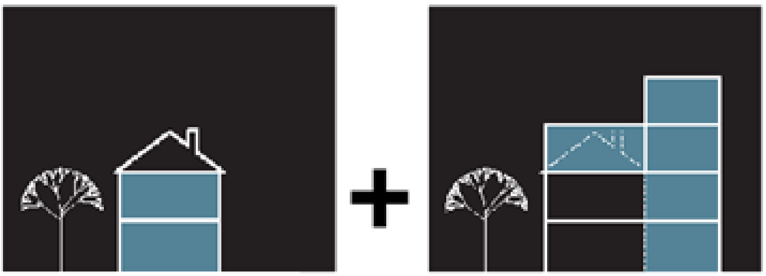


Figure 5.31- This diagram illustrates the process of adding volumes to an existing building. Source:(image courtesy of Grape Architects

Acquiring and processing workflows:

Figure 5.32 shows the schematic diagram of the acquisition and processing workflows and the case study steps sequence, described in the next paragraphs.

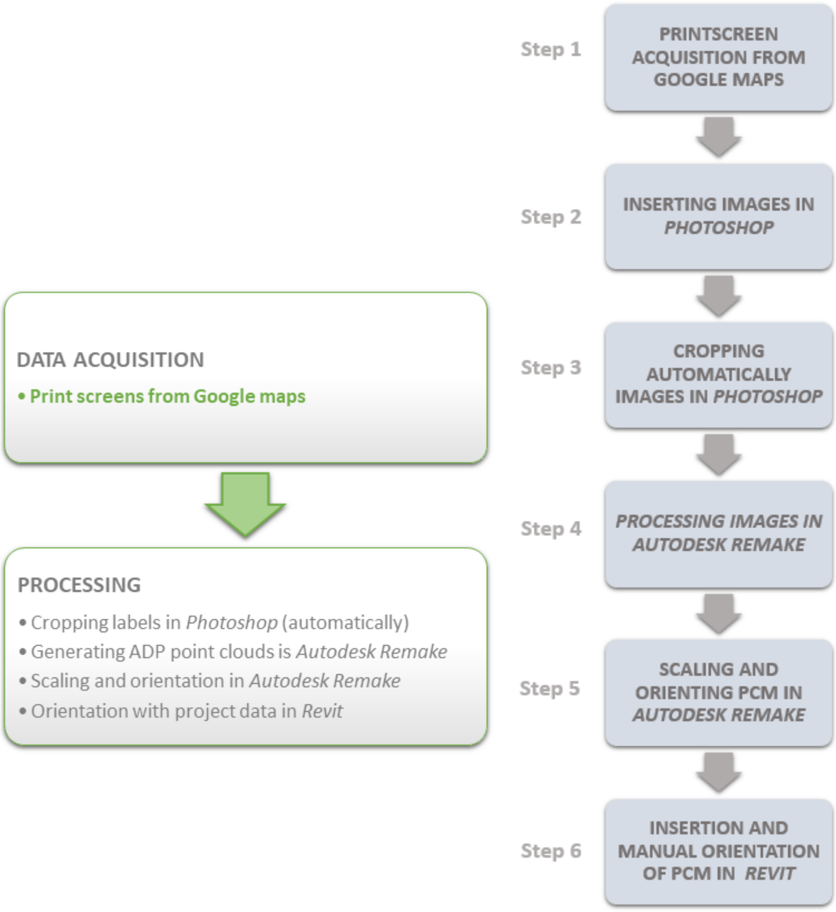


Figure 5.32-Schematic diagram of the acquisition and processing workflows and the case study steps sequence

To obtain low accuracy data of a specific site, one can open google maps for example, choose the 3D model option without labels and start taking print screens while rotating the model, this workflow can be found in a youtube video from Arne Bjelland[33] from where the following description was extracted. This process can result in hundreds of images of a site. In order to obtain just the image without search tab or symbols (Figure 5.33), one can use a software similar to Photoshop, create an “action script” to crop the image and apply it to all the images.

[33] https://www.youtube.com/watch?v=qnEYrDN8660

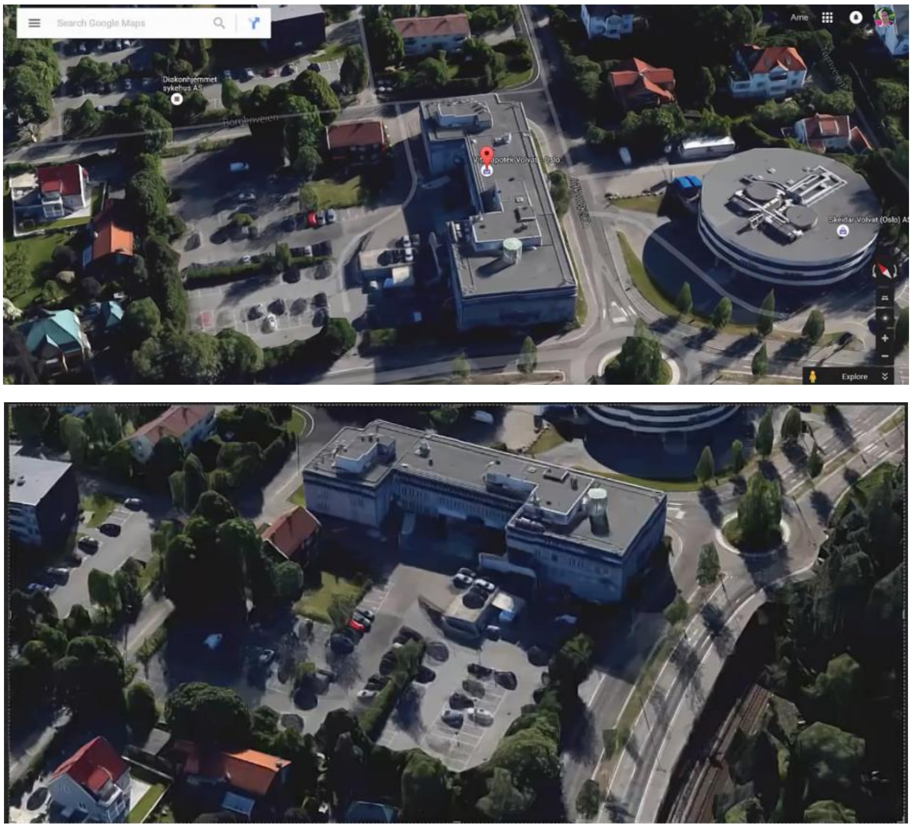


Figure 5.33- Top image: example of a print screen of :google maps 3D model with symbols; bottom image: example of a cropped image

This process generates “low quality aerial images” that can be inserted in photogrammetric software to generate the PCM (Figure 5.34).

Figure 5.34- example of PCMs generated through google maps print screens

This is then scaled and oriented. To do this, one should rotate it to true north and insert a known measure of the object being studied. Figure 5.35 shows the building being measured in google maps on the left so that one can apply the same measure on the PCM on the right.

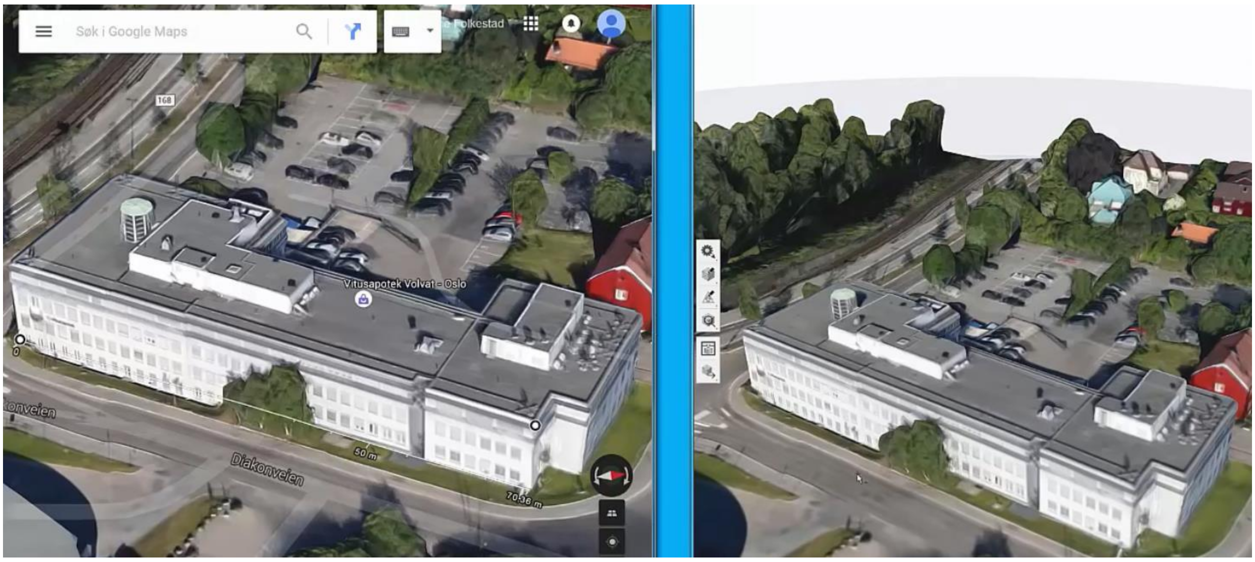


Figure 5.35 - Left image: measure on google maps; Right image: PCM being scaled.

Initially, I was doing this process in *Autodesk® Remake®* (software used for the above figures) but I find *CloudCompare* more interesting to use for scale and orientation since I have more control of the tools and it is freeware.

Once the PCM is scaled and oriented, it is inserted in *Autodesk® Revit®*, Figure 5.36. Once this is done, one can start developing volume studies with this data.

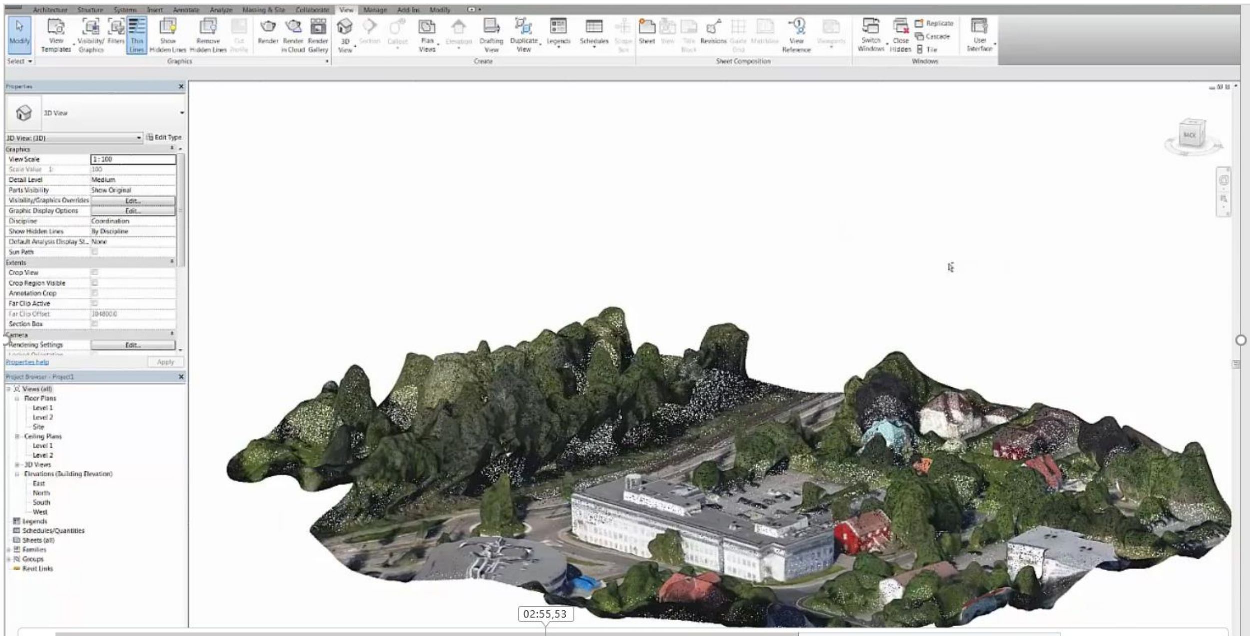


Figure 5.36- Photogrammetric google maps PCM in *Autodesk® Revit®*

Critical analysis of workflow and outputs

Figure 5.37 shows an example (from a different project but produced with the same workflow) of the low accuracy PCM inserted in *Autodesk® Revit®.* We can observe the PCM integrated with volume studies on the top. This process allows to simulate multiple options, understanding their consequences and simplifying the communication of the architect intentions.

Figure 5.37- low accuracy PCM with a volume option on top

This workflow was used by Margarida Barbosa at Grape Architects on a daily basis for different volume studies. The software used to generate the PCM was *Agisoft PhotoScan,* the reason for changing software derived from the few options in *Autodesk® Remake®* to control the output result and hassle in transforming the scale and position. Once the model is scaled for the first time, if one was not able to choose the right points, it is a trial and error process to obtain the correct point's distance and consequently the PCM scale. Another software considered was *Pix4D* but the software price was too high for the desired use, a low cost process for conceptual studies.

5.1.2. Using 360° panorama photos as complementing information for modeling

College Station Theater |Houston, TX |The Beck Group

Project goal:

This project was the interior refurbishment of a cinema building (Figure 5.38). The idea was to change minor elements, not to intervene profoundly on the building. In this project, the project team needed a model that was a simplification of reality. When modeling, it is important to check information that is not clear or visible in the information we are basing our model on, whether it is a CAD drawing (dwg) or a PCM, for example. Often are photos stored in local folders on the computers in architectural offices, associated with the folder where the project information is. Then, whenever in doubt, the person modeling the project goes to the photo folder and searches through it until finding the photo containing the information needed. Sometimes there can be 300 photos and this could be a time consuming process. One way of complementing the information and improving this process can be through linking 360° photos with a plan. This can be done through a web platform called Holobuilder[34], for example.

Figure 5.38 - College Station Theater. Source: Google maps.

Acquiring and processing workflows:

Figure 5.39 shows the schematic diagram of the acquisition and processing workflows and the case study steps sequence, described in the next paragraphs.

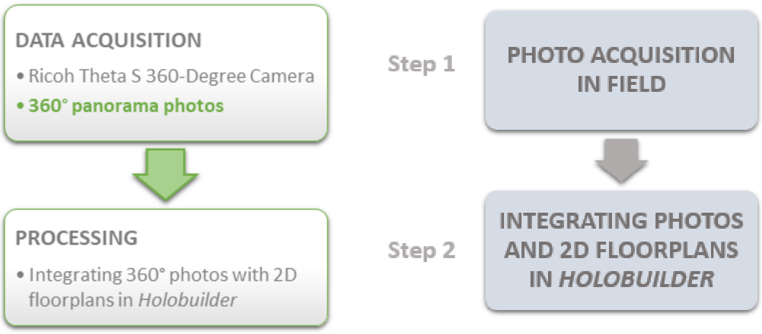


Figure 5.39- Schematic diagram of the acquisition and processing workflows and the case study steps sequence

The capture of the 360° panorama photos was done, by the project team, through a 360° camera (the Ricoh Theta S 360-Degree Camera) fixed on top of a hard construction hat, shown in Figure 5.40. The surveyor walked through the building while taking the photos through an app on his phone.

[34] https://www.holobuilder.com/

Figure 5.40- 360° camera fixed on top of a hard construction hat. Source: Image courtesy The Beck Group

The photos are then inserted in Holobuilder, together with a floorplan of the corresponding level. One can create marks on each room corresponding to the place where the photo was taken and associate them. Once this is done, we go through the floorplan and click on the marks which are linked to 360° photos, taking the viewer directly to it. Figure 5.41 shows two images that have on the left corner the floor plan with the marks, where the blue/orange circle mark corresponds to the mark clicked and positions the viewer; the 360° photo that the viewer is observing corresponds to this blue/orange mark.

Figure 5.41- *Holobuilder* web platform view of 360° photos. Source: Image courtesy The Beck Group

One can walk through the photos in a "virtual" visit while understanding the photo location in the building floor plan. This promotes the perception of building spaces and their relations.

<u>Critical analysis of workflow and outputs</u>

This process allows a quick and efficient way of checking visual details when modeling. It also organizes photos, connecting them with project data. They are no longer isolated information but become an information set that allows to establish relationships between them.

Project goal:

This project started by being a Grape Architect's study and became a refurbishment project, after agreement with clients. Since it was considered a listed building, an accurate survey was needed, as well as historical documentation of the building state. The BIMs was originally generated through CAD drawings and needed to be adjusted to the PCM acquired subsequent to it. Figure 5.42 illustrates the building in study.

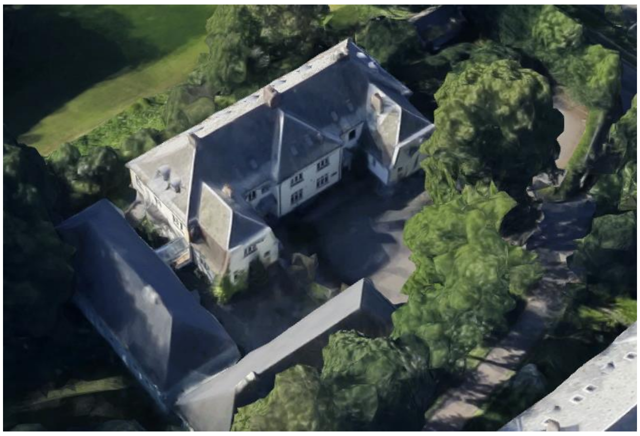


Figure 5.42 - Sognsveien 9A building. Source: Google maps.

The interior scan data was acquired without color, and the team during the modeling process felt the need of consulting photos and different kinds of information that would promote the correct information modeling. Another way of organizing photos and helping the modeling process through the visualization of a 3D model is to create a 3D model through Matterport Pro 3D Camera (Figure 5.43). This is a 360° camera associated with infrared laser technology, that is controlled through an iPad app (Matterport app) to capture 3D and 2D images of an interior space.

Figure 5.43- Matterport Pro 3D Camera [35]

[35]https://static1.squarespace.com/static/52c5be94e4b0332a70752da8/t/5596d713e4b0892edbf8fa47/1435948820046/Matterport+Pro+3D+Camera-Photo

Acquiring and processing workflows:

Figure 5.44 shows the schematic diagram of the acquisition and processing workflows described in the next paragraph.

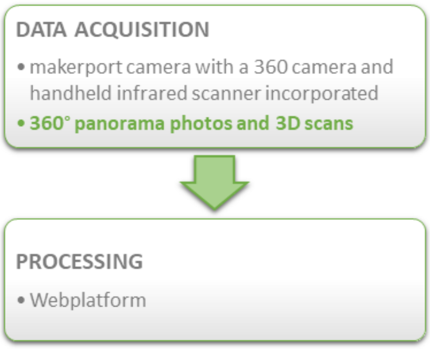


Figure 5.44- Schematic diagram of the acquiring and processing workflow sequence

The acquisition was done by a company external to the office. The camera rotates on a tripod placed in several positions (like the TLS technique) where it emits an infrared laser and collects 360° photos. The final product is a web platform with a 3D mesh model that has 360° photos associated to each room (Figure 5.45). The 3D mesh model has circular marks that correspond to links for the 360° photos. These links are also present inside the 360° images, so it is possible to "walk to" the next 360° photo. This is very helpful to consult while modeling to see the details and information not available before.

Figure 5.45- top Images: 3D mesh model; bottom image: 360° photos associated to each room. Source: image courtesy Grape Architects

Measurements in Matterport are generally accurate to 1% of reality under normal conditions (interior rooms, without a lot of visual obstructions). This means that in a 10 meter long room, measurements are accurate up to 10 centimeters. In addition, objects smaller than 2.5 centimeters in any dimension may not appear.

5.2. Handling high modeling/conversion effort

In the architectural field, the general practice to create as-built BIM is majorly a manual process. It is a costly, time-consuming, subjective, and labor-intensive process. It requires skilled workers whose decisions, about exactly what elements to model and how to model them, are subjective, resulting in variability of the model quality. The workflow is also supported by several software tools, resulting in the loss of information, due to the limitations of data exchange standards (Chapter 3 and 4), which lead to data interoperability problems. Furthermore, existing standards and methods for representing BIMs were developed primarily to support models derived from new buildings design data, and the requirements for representing as-built BIMs are somewhat different from the representation needs for as-designed BIMs (Chapter 4).

In addition to the issues generated by the implementation of new AEC workflows, with new software and having the same standards across different companies and teams that work together, the difficulty of as-built BIMs creation and the limitations in representing them are major obstacles for its usage and development in the industry.

Section 5.2. addresses how to handle the high modeling effort for as-built BIM (illustrated in Figure 5.46).

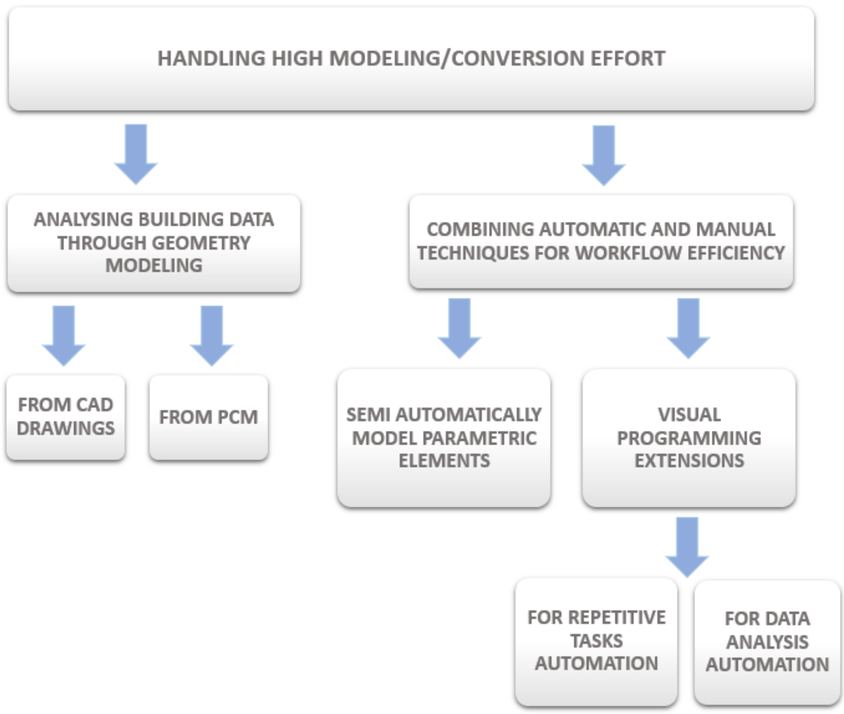


Figure 5.46- Schematic diagram of the Section 5.2 subject sequence

As observed, Section 5.2 is subdivided into two sections: Section 5.2.1, focus on critical analysis of BIMs generated through PCM or CAD drawings, and in the description of modeling (geometric analysis) workflows; and, Section 5.2.2. that outlines how automation can replace repetitive tasks reducing the modeling effort.

5.2.1 Building geometry analysis workflows

The most common as-built BIM workflow is to trace BIMs over CAD plans or PCM inserted in the software for managing information (*Autodesk® Revit®, Archicad®*, among others). Both workflows start with the insertion of the CAD data or PCM which is used as a base to start modeling.

A. Critical analysis of BIMs generated through CAD drawings: comparison with PCM

Ruseløkkveien project |Oslo, Norway| Dark Arkitekter

This is the same project addressed in section 5.1.1., where we saw how data can be generated to complement missing information for modeling. This section focuses on the evaluation of the BIMs elements, comparing them to the PCM.

Project goal:

The project goal was the refurbishment of the facade and adjacent shops (Figure 5.47). This project was based in CAD drawings supplied to the office. During its development there were some issues with missing information and conflict of information and the team needed to check the facade stone pavement heights. To solve this issue, a survey company was hired to execute a TLS survey with the corresponding survey control network. The ADP data posteriorly acquired is not taken in account in this section.

Figure 5.47- Ruseløkkveien shops facade. Source: Google maps

Acquiring and processing workflows:

Figure 5.48 shows the schematic diagram of the survey and data analysis workflows described in the next paragraphs.

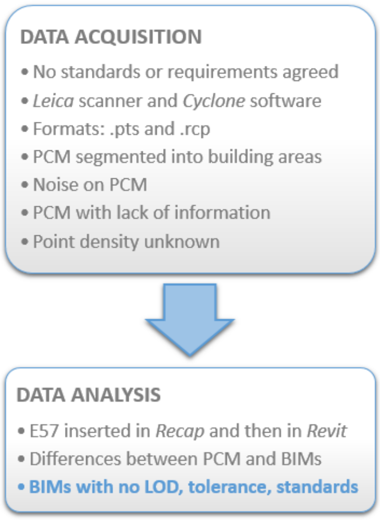


Figure 5.48- Schematic diagram of the survey and data analysis workflows sequence

The survey was done with a Leica scanner associated with control survey and the data was registered in *Leica Geosystems Cyclone*. The computer capacity used was an Intel Core i7 4700MQ @2.4 GHz with 24 GB ram. The operating system was 64 bit windows 7.

The company required a PCM without color. There were no more requirements and the data consisted of sets of .pts and .E57 files. The architects were having difficulties in understanding the point cloud data and relating it to the existing BIMs. I was asked to analyse the PCM, compare it to the BIMs and adjust BIMs elements to the PCM since the PCM had more coherent and up to date information than the CAD drawings.

Modeling workflow:

The PCM was divided in sections and parts, because *Autodesk® Revit®* performs best with small size linked files, which can be loaded and unloaded. Once the team received the raw files, they were imported into *Autodesk® Recap®* and converted into .rcp format. Ruseløkkveien project has eight .rcp files inside *Autodesk® Revit®*, resulting from the segmentation of the original PCM, as observed in Figure 5.49. Each segment (point cloud file) corresponds to a building area.

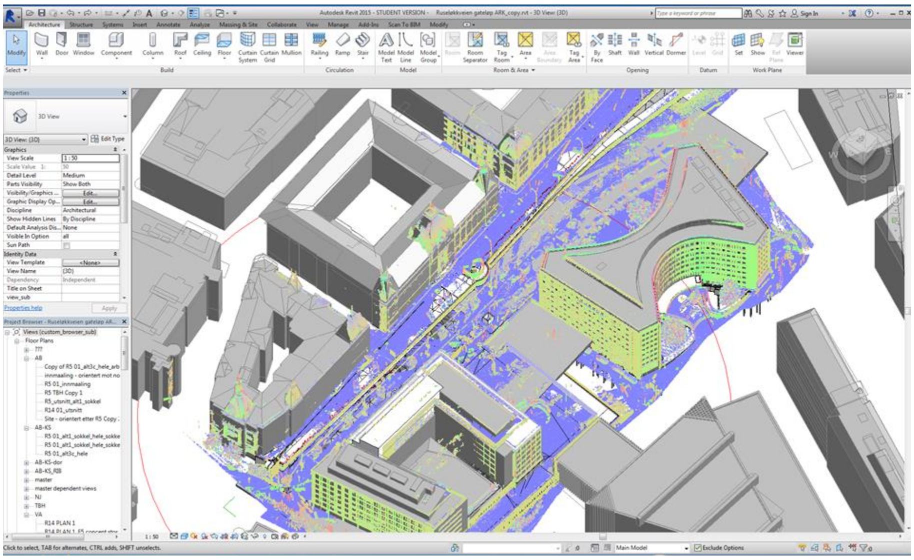


Figure 5.49- Ruseløkkveien Point Cloud model. Source: image courtesy Dark Arkitekts

The point cloud files have unwanted information (noise) like cars, people and scaffolding, which can be observed in Figure 5.50. In this specific PCM, points corresponding to this information should have been removed before because they hinder visualization and interpretation of the building elements points.

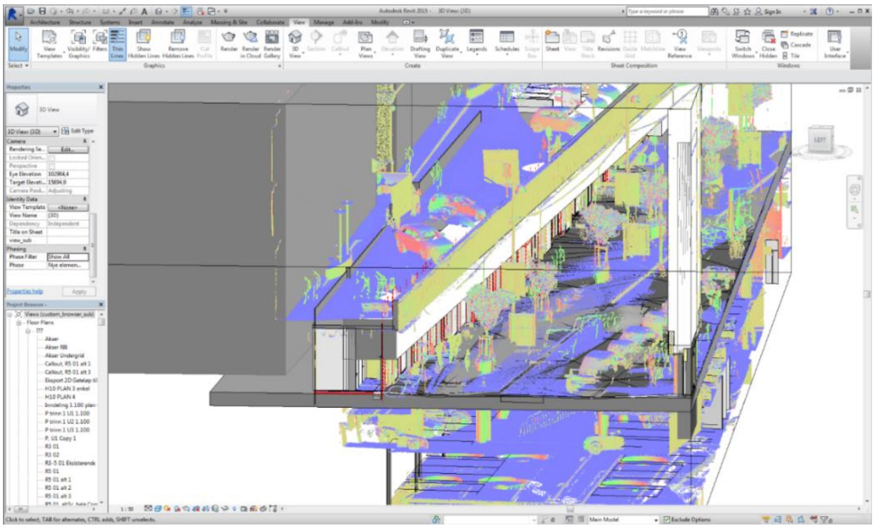


Figure 5.50- Unwanted noise on Point Clouds.. Source: image courtesy Dark Arkitekts

The point density of point clouds in this project allowed *Autodesk® Revit®* to efficiently deal with them, resulting in a fast orbit and visualization of the model. It allows the modeling of the general shape of the buildings, but when applied to the modeling of details, these point clouds do not provide enough information (in this specific case it would probably have been solved with more scans in the areas where information was missing).

In Figure 5.51 the rectangle outlines one part of a balustrade that has few points to properly model its panels. They vary in size and thickness and the inexistence of points leads to the assumption of information and consequently inaccurate results.

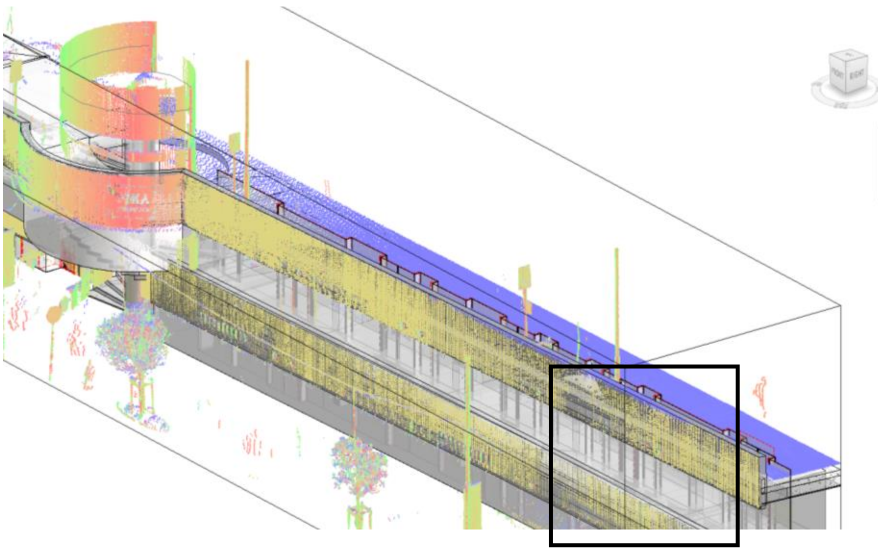


Figure 5.51- Lack of points in some areas of the point cloud model. . Source: image courtesy Dark Arkitekts

The BIMs were not originally created from point clouds but from existing 2D drawings and was progressively corrected, without modeling tolerances. Some parts of the BIMs were already adjusted, while others still needed to be adjusted. Some elements were in a different position when compared with the PCM, as can be seen in the example in Figure 5.52.

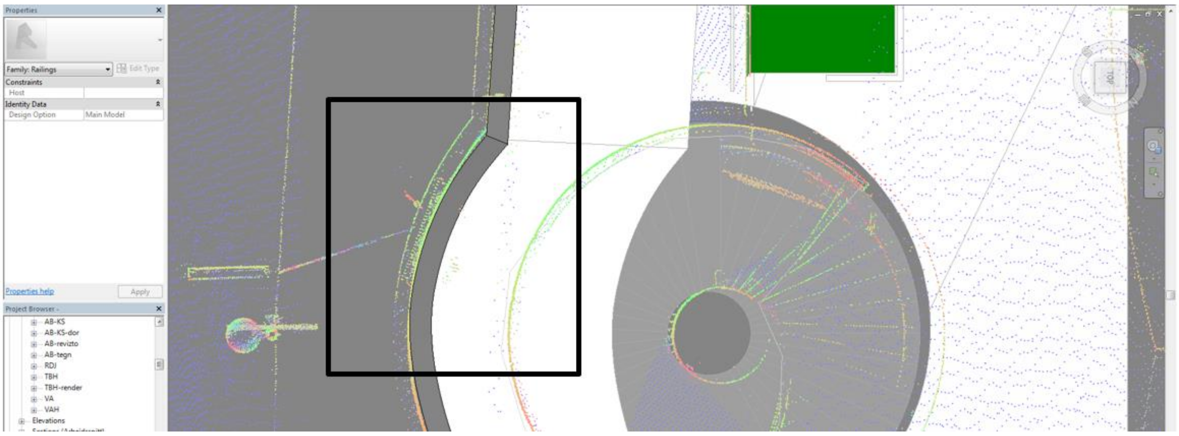


Figure 5.52- Balustrade object not placed where the point clouds represent the existing balustrade. . Source: image courtesy Dark Arkitekts

Considering the PCM was the most updated and accurate data to base decisions on, it was observed that some elements were incorrectly represented when compared with the point clouds. In Figure 5.53, we can observe that the modeled stair's diameter does not correspond to the diameter represented in the point cloud.

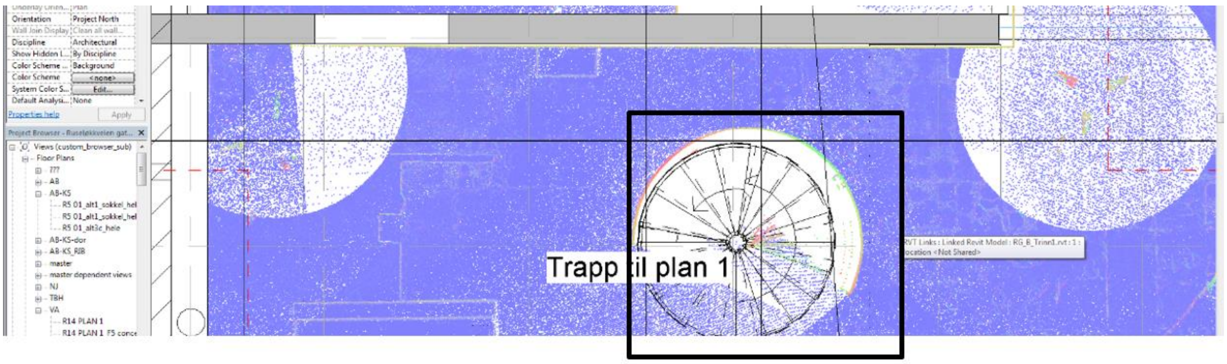


Figure 5.53- Modeled Stairs have a different diameter from the one in the point clouds. . Source: image courtesy Dark Arkitekts

Horizontal or vertical deviations of elements, like deformation of slabs or slight slopes are not represented or registered in the model. This can result into wrong design decisions during project development that have to be rethought later (design and construction errors). Figure 5.54 shows the difference between the point cloud survey and the modeled floor, where the highest value measured was approximately 100 millimeters.

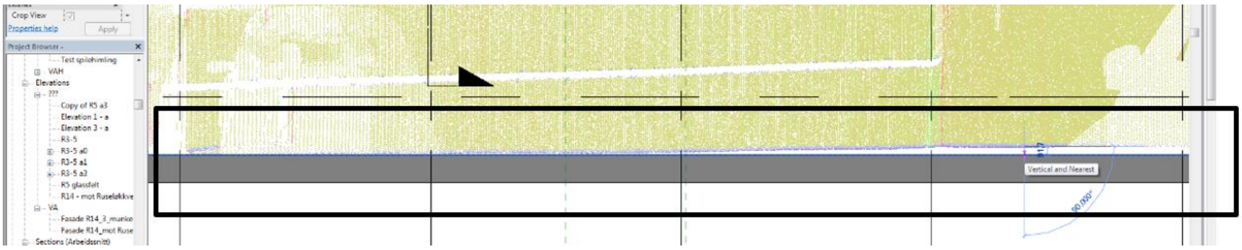


Figure 5.54- Modeled floor that differs from the slope observed in the point clouds. Source: image courtesy Dark Arkitekts

Critical analysis of workflow and outputs

In this project, the PCM was segmented into building areas which contribute to a good software performance. The PCM should have been cleaned (removing cars, people, etc.). The culling of unwanted data would have contributed for better data understanding. Also there were important building areas where information was lacking or had insufficient detail, which outlines the need to communicate the project goal to the survey team so they plan an efficient survey, acquiring the essential data.

The vertical and horizontal deviations/deformations of building elements were not annotated in the BIMs since they are not present in the CAD drawings. This is important information that should be present when dealing with interventions in existing buildings.

The comparison of PCM with BIMs outlined the need for updated and accurate information when starting modeling for an intervention. The basis used for the BIMs did not correspond to the as-built data, which results in the need of adjusting the model. The adjustment is time consuming and it is double work that increases the price of the intervention. It also resulted in the lack of modeling tolerances or high tolerances observed when comparing the BIMs elements dimension and position with the PCM.

Sognsveien | Oslo, Norway|Grape Architects

Figure 5.55 shows the schematic diagram of the survey and data analysis workflows described in the next paragraphs.

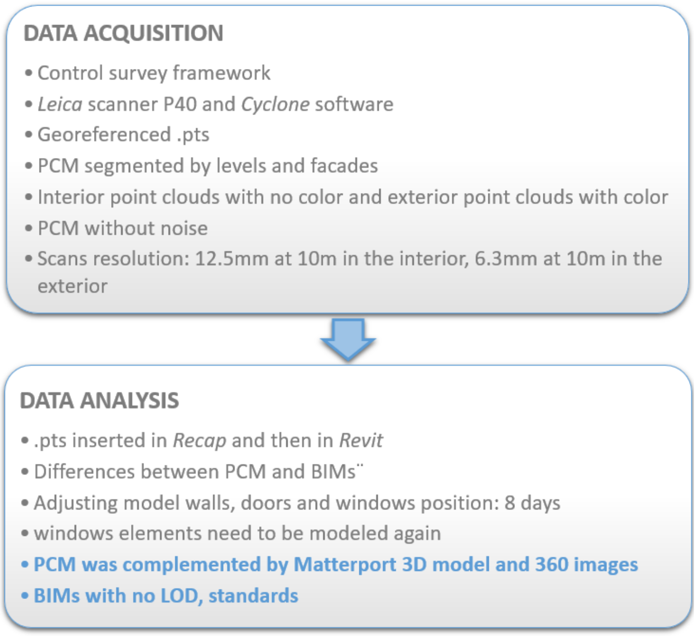


Figure 5.55- Schematic diagram of the survey and data analysis workflow sequence

The project used in this section was also used in Section 5.1.2. for the use of information, the 360° panorama photos, to complement missing information for modeling. This section focuses on the evaluation of the BIMs elements, comparing them to the PCM.

<u>Project goal:</u>

This project was a refurbishment intervention that was initially a study of possible building intervention. In the initial study, the budget did not allow to invest in a 3D survey so the solution was to generate BIMs from existing CAD drawings. These drawings weren't updated but contained the general building information needed to begin the study. When it became a refurbishment project, and since it was considered a listed building, an accurate survey was required as historical documentation of the state of the building. Figure 5.56 shows the building being studied.

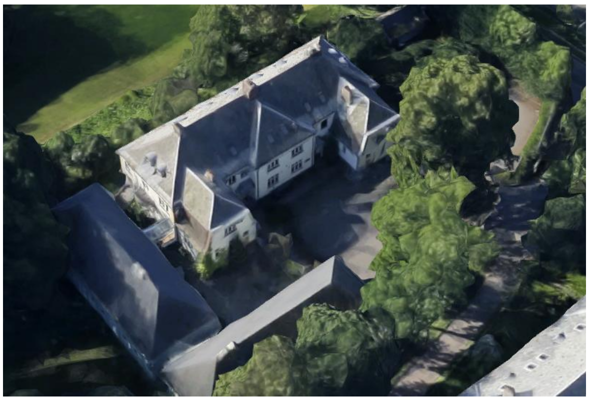


Figure 5.56 - Sognsveien 9A building. Source: Google maps.

Acquiring and processing workflows:

A survey company scanned the interior and exterior of the building with a Leica P40 and ground control points. The survey resolution was 12.5mm at 10m indoors and 6.3mm at 10m outdoors. The delivery included georeferenced .pts files splitted by level and the facades with exterior. The interior point clouds were scanned without color while the exterior facades were RGB-colored scans.

Modeling workflow:

Figure 5.57 shows the initial *Autodesk® Revit®* model obtained through CAD drawings.

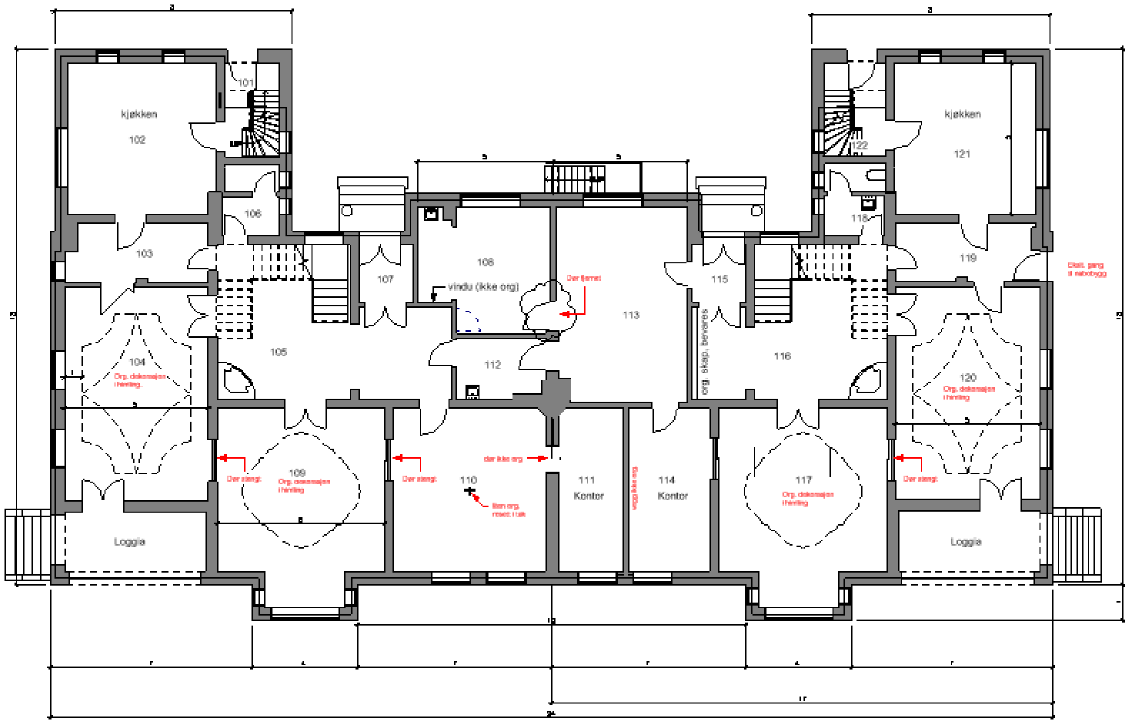


Figure 5.57 - BIMs generated through CAD drawings. Source: image courtesy Grape Architects

Figure 5.58 shows the same model with the PCM, where we can observe multiple differences between the BIMs and the PCM. Elements, like walls and columns, can differ up to 40cm in their position in the BIMs and PCM, or not be correct at all.

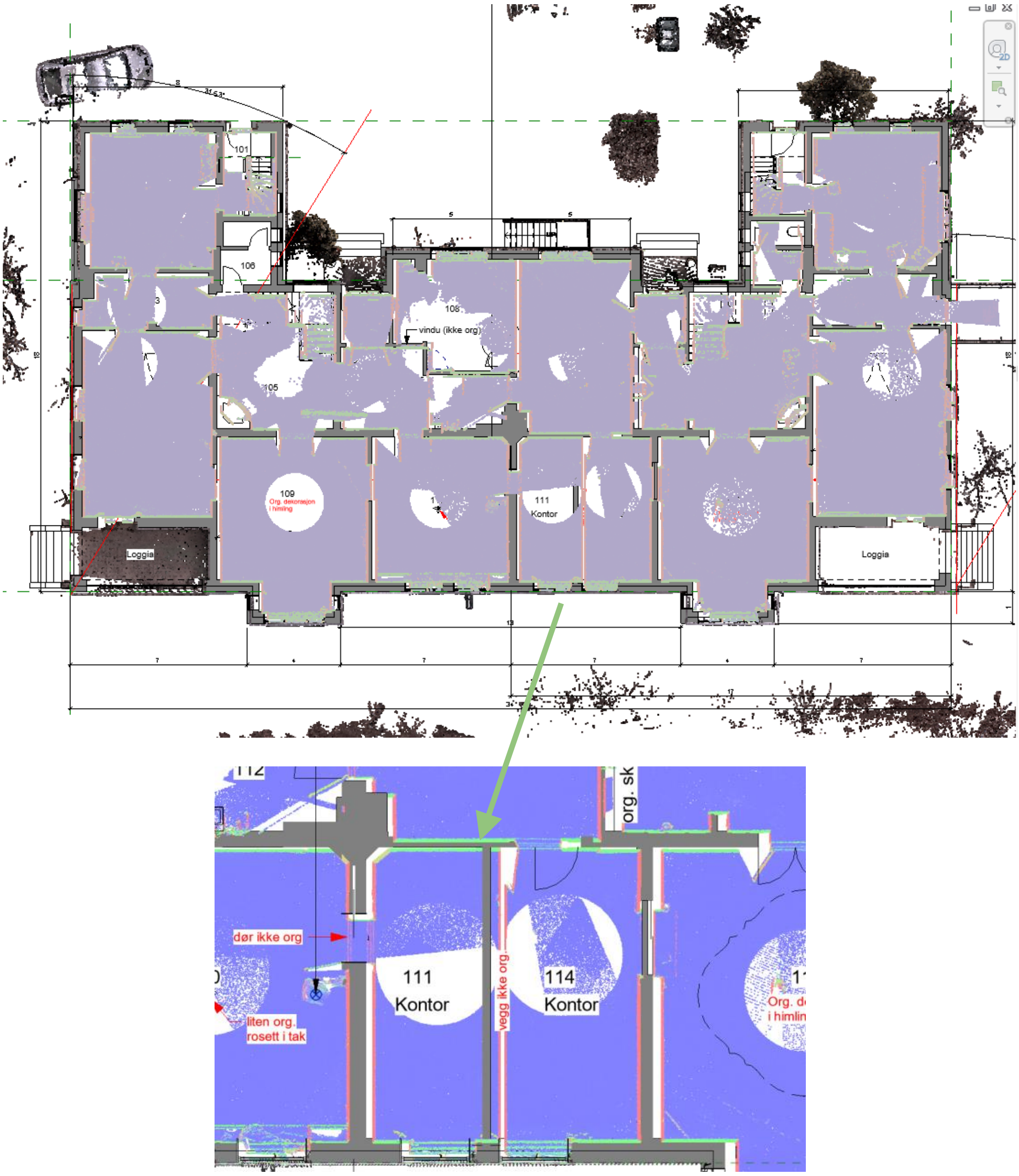


Figure 5.58- This images illustrate the differences between BIMs walls and windows from the PCM. Source: image courtesy Grape Architects

The adjustment of the elements with the PCM information respected the following references:

- Prior to elements adjustment, reference planes were drawn orthogonally and within 5 mm tolerance from the origin, with even dimensions. Elements were measured from one face of the element (for example one side of the wall) to the reference planes. “Snap to Point Cloud” technique was not used since it hinders the use of tolerances, instead, manual input of measures was used to move the elements;
- Elements were adjusted within 5 millimeters from the PCM where possible and where sufficient data was available.

Each BIMs element had to be checked in the floorplans and sections to assure these guidelines were being followed not only horizontally but also vertically throughout the model.

Manually adjusting the model was a time consuming process that took 8 days just for the wall, door and window positions in the floor plans. The shape and type of windows had to be completely changed, as shown in Figure 5.59, however this process is not included in the time counting.

Figure 5.59 - These images illustrate the differences between BIMs windows and the PCM windows. Source: image courtesy Grape Architects

Critical analysis of workflow and outputs

It is possible to generate BIMs from CAD drawings using them as the basis information to manually extract the 3D building components. The restriction is that, usually, the model will not be a description of the state of the facility exactly as it is (as-is condition) or as it was built (as-built conditions) but as it was intended to be in the design project (as-designed condition). Also the possible unregistered changes of the project, inaccuracies of drawings or the building changes resulting from the facility's lifecycle could lead to an incorrect representation of the facility.

Adjusting the BIMs elements to the PCM is a time consuming process. One needs to double check every element and it is difficult to keep tolerances while adjusting elements. This is due to the bi-directional associativity BIM feature, that consists in the parametric elements associations with nearby elements. This means that, when a wall is moved, it will also move the nearby walls/elements connected to them, often without the user noticing. A solution for this issue can be to fix the element's position but it will still be a laborious task.

To model an as-is or as-built BIMs, usually the most updated and accurate information is the 3D data, resulting from TLS and ADP surveys.

B. Critical analysis of BIMs generated through PCM

Karl Johans Gate 8-10 project |Oslo, Norway| Dark Architects

Project goal:

The project consisted in the refurbishment of ground floor shops and an office building(Figure 5.60). In this project the team asked me to analyse the BIMs delivered by a survey company, documenting how it was done and if it could be improved.

Figure 5.60 - Karl Johans Gate 8-10 buildings. Source: Google maps.

Acquiring and processing workflows:

Figure 5.61 shows the schematic diagram of the survey and data analysis workflows described in the next paragraphs.

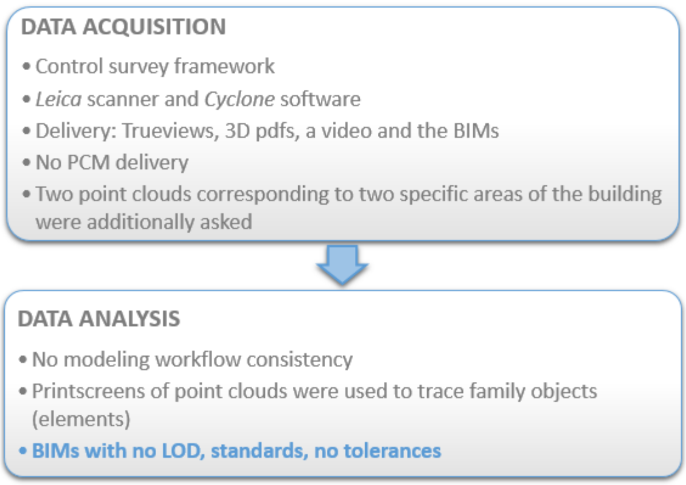


Figure 5.61- Schematic diagram of the survey and data analysis workflow sequence

The TLS survey was done with a Leica scanner and the data was registered in *Leica Geosystems Cyclone*. The computer capacity used was an Intel Core i7 4700MQ @2.4 GHz with 24 Gb ram. The operating system was windows 7 64 bit. The survey company in this project delivered different types of data: Truviews, 3D pdf, a video and the BIMs. No PCM was delivered.

A TruView web-based portal was delivered allowing a visual tour of the scanned site, through the visualization of the unified point clouds. We have access to the webpage containing the map of scans represented by yellow triangles (Figure 5.62).

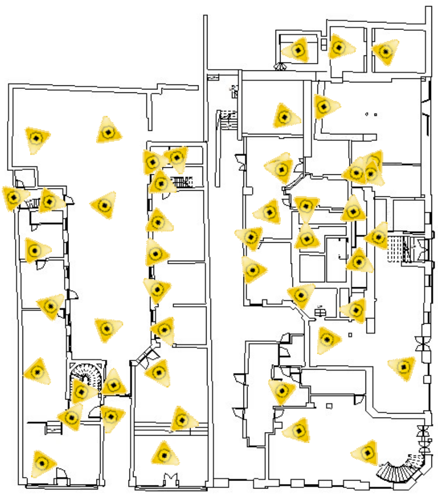


Figure 5.62- TrueView webpage containing the map of scans. Source: image courtesy Dark Arkitekts

Each of these triangles is a link to the corresponding 3D point cloud obtained by a scan. These point clouds allow visualizing and analyzing the building in question and extracting 2D reflectance images (e.g. Figure 5.63).

Figure 5.63- 2D reflectance image of the 3D Point clouds. Source: image courtesy Dark Arkitekts

The Truview is a web platform for visualization, similar to the described process to complement existing information during modeling in Section 5.1.2. A 3D PDF was delivered as well (Figure 5.64), allowing to visualize the 3D model and level sections integrated in the 3D, as well as different perspectives of the model; and a video (.mp4) of a model walkthrough.

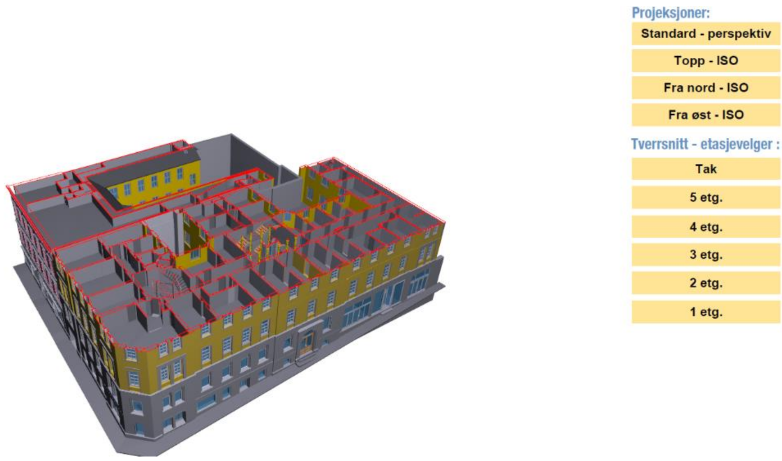


Figure 5.64- 3D PDF of the building model. Source: image courtesy Dark Arkitekts

Critical analysis of workflow and outputs

The TruView viewer tool in addition to the BIMs were not enough to understand and intervene in all the building areas. During the design process the team needed more information related to specific areas and asked for point cloud data of those building areas. These two point cloud files were included in the BIMs (Figure 5.65).

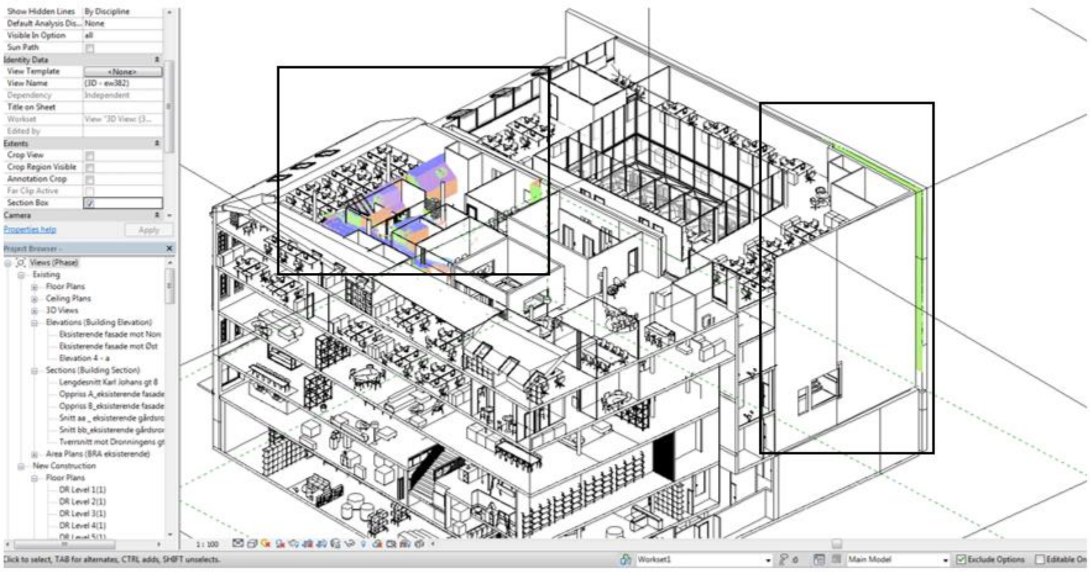


Figure 5.65- Visualization of selected point cloud areas within the Autodesk® Revit® model. Source: image courtesy Dark Arkitekts

It was observed in the building information model that similar elements, like window frames, were modeled differently. They were modeled as non-parametric objects, with limited capacity of transformation, and, as observed in Figure 5.66, they differ in the extrusions they contain; some frames containing the window sill, while other frames stand apart from the window sill.

Figure 5.66- Same type of object contain different parts of the real element. Source: image courtesy Dark Arkitekts

There is no LOD (see Section 4.2.2) agreed regarding the model received from the survey company. In this BIMs, some building elements were included with a high level of graphical detail, while others are not even represented. The combination of the two has a high impact on the visualization of the building. An example of this is Figure 5.67, where the presence of stone stereotomy is missing (on the right) but the circles of the frieze are represented (on the left).

Figure 5.67 - No LOD established: representation of small elements and occlusion of set of elements that influence the visualization of the façade. Source: image courtesy Dark Arkitekts

The LOD and what is important to represent should be established as part of the agreement with the survey company. Figure 5.68 shows frieze elements that visually mark the facade and are not represented in the model.

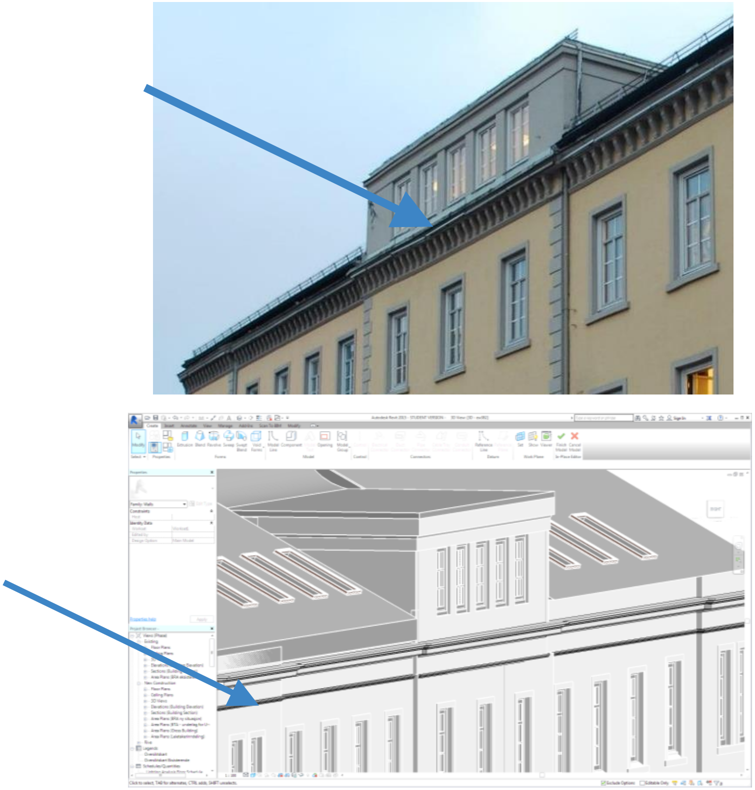


Figure 5.68 - Occlusion of a set of elements that influence the visualization of the façade. Source: image courtesy Dark Arkitekts

Building elements modeled as parametric objects in the *Autodesk® Revit®* family editor were created through point cloud print screens from the *Leica Cyclone* software. They were used by the survey company as templates to extract the elements main measures and generate reference planes (Figure 5.69). These are then used to model the element.

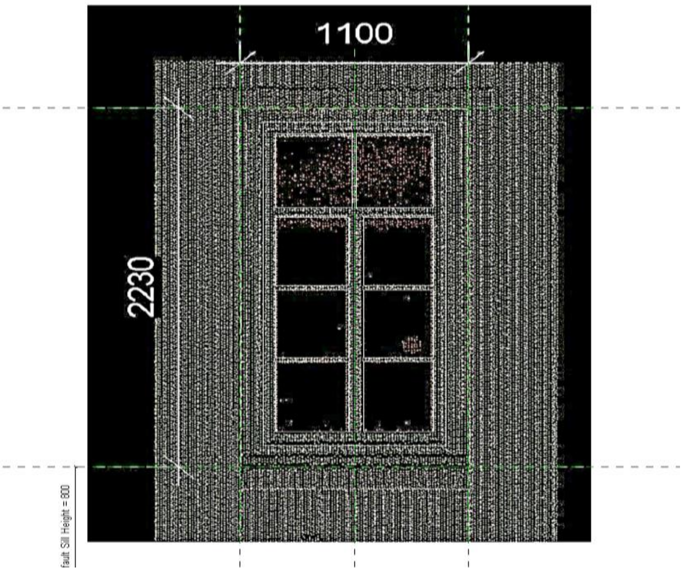


Figure 5.69 - Print screen of the point clouds used to create the window objects. Source: image courtesy Dark Arkitekts

The LOD should be discussed and agreed prior to modeling. Figure 5.70 shows an example of element simplification and interpretation. It should be discussed beforehand to what extent the proposed interpretation fits the project team interests.

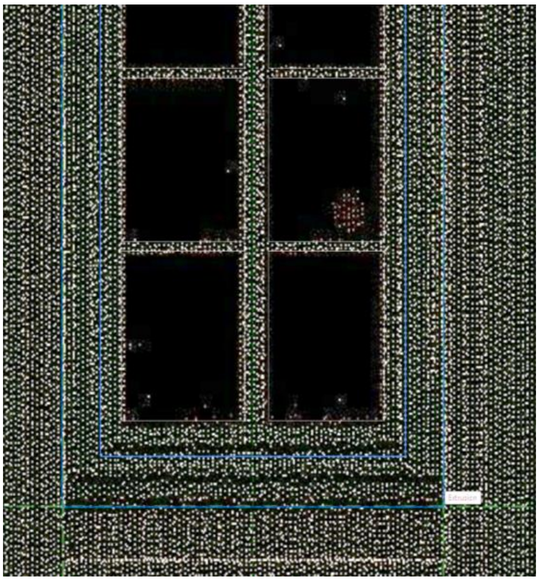


Figure 5.70- Zoom of the print screen in figure 18; element simplification and interpretation. Source: image courtesy Dark Arkitekts

In Figure 5.71, we observe a print screen of the element section used as a template for the window profile modeling.

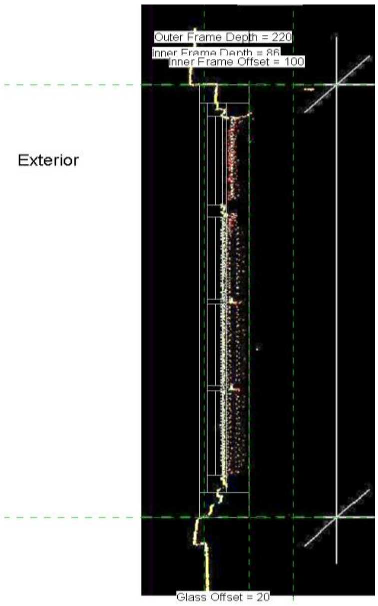


Figure 5.71- Print screen of the window section. Source: image courtesy Dark Arkitekts

What can be observed is a lack of quality in the template image used (points in Figure 17) when comparing to the PCM data, and the high level of tolerance and simplification used when representing window elements (lines in Figure 5.72).

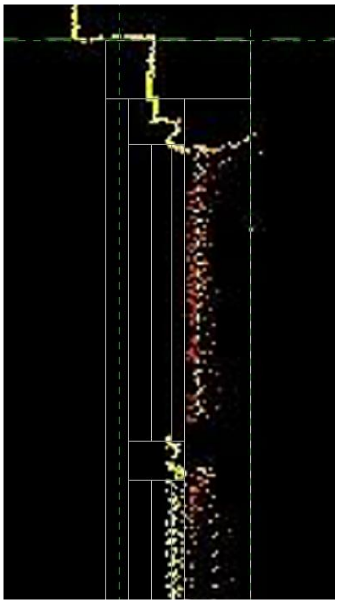


Figure 5.72- Zoom of the print screen in figure 20; element simplification and interpretation. Source: image courtesy Dark Arkitekts

The points corresponding to the building windows should be compared in the PCM and the one that represents the average of them should be segmented and exported into a point cloud .dxf file format. This format can be inserted in the *Autodesk® Revit®* family editor file, which would provide a more accurate representation and allow the user to check the data from which the element was modeled.

The element simplification should be done through reference planes based on the point cloud main measures, respecting the agreed tolerances and with even dimensions.

Akersgata 35 project |Oslo, Norway|Dark Arkitekter

Project goal:

This project was a refurbishment of an office building with shopping in the ground floor (Figure 5.73). In this project, the team asked to analyse the BIMs delivered by a survey company, documenting how it was done and if it could be improved.

Figure 5.73 - Akersgata 35 building- Left image: before intervention, Right image: when intervention started. Source: Google maps.

Acquiring and processing workflows:

Figure 5.74 shows the schematic diagram of the survey and data analysis workflows described in the next paragraphs.

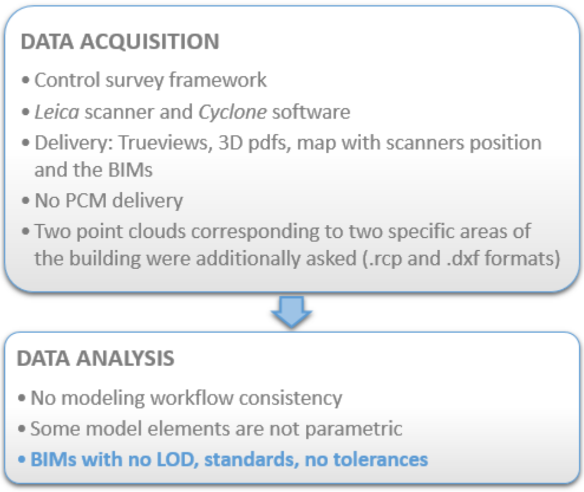


Figure 5.74- Schematic diagram of the survey and data analysis workflow sequence

In Akersgata project, the survey company delivered different types of data, namely a 3D pdf, a video .mp4 of the model walkthrough, a TruView web-based portal and, a map in pdf with scan positions but without identification of scans (Figure 5.75) and a BIMs.

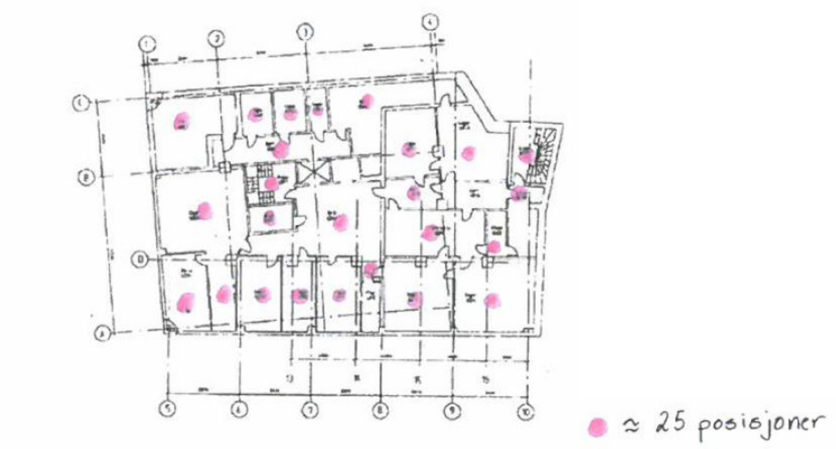


Figure 5.75- Pdf with a map of scan positions. Source: image courtesy Dark Arkitekts

During project development, PCM data was asked by the engineer, since they were not using the BIMs. Also scans after demolition were requested in order to better understand what remained and to retrieve data about the invisible material layers of the building. The Dark architecture company usually orders from a survey company: first a BIMs of the building and after demolitions during construction, point clouds files of specific areas, to understand materials and if the project is being constructed as designed.

Critical analysis of workflow and outputs

In this project, during the project development in BIMs, a set of .rcp files was received, corresponding to horizontal level sections of the point cloud model and the corresponding .dxf. Two point cloud horizontal PCM sections were inserted in the *Autodesk® Revit®* project, corresponding to different levels of the building (Figure 5.76).

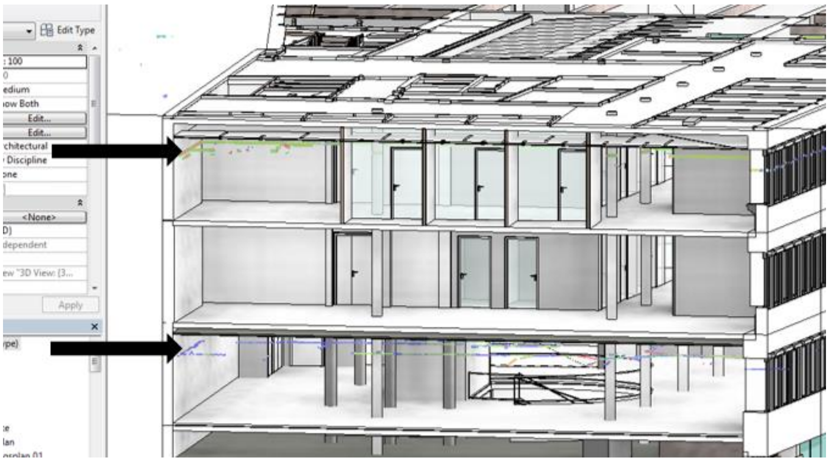


Figure 5.76- Visualization of the two point cloud sections within the Autodesk® Revit® model. Source: image courtesy Dark Arkitekts

These sections were used to confirm the position of model elements, in relation with the 3D survey, during BIMs development. They also allow to check for unwanted and unnoticed element movements (that were not fixed with the *Autodesk® Revit® "*pin" tool). Finally, such sections allow to visualise also new elements that were not on the scope of work. This PCM section allows a general geometric framework for modeling, but the user cannot understand element connections and the building condition. It is restricted to the area of the section (Figure 5.77) and it is limited information regarding what could be seen if the whole PCM was included.

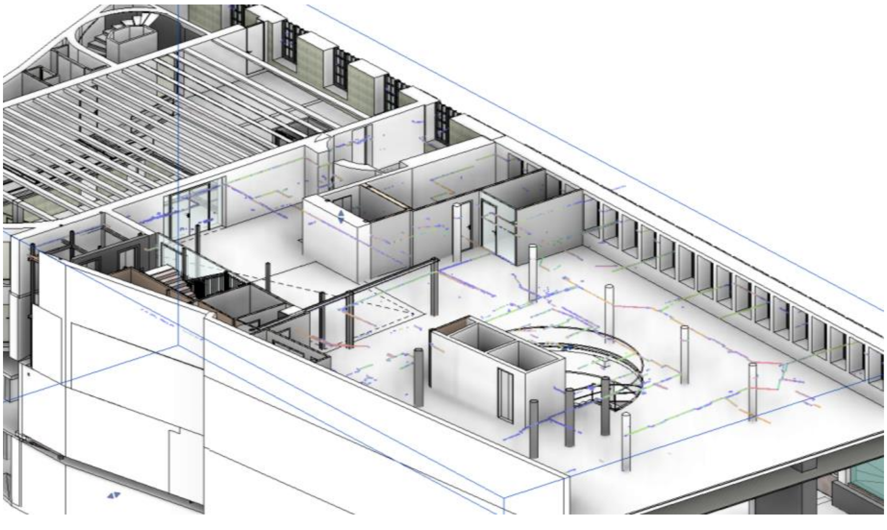


Figure 5.77- Visualization of a point cloud section and its corresponding level. Source: image courtesy Dark Arkitekts

Figure 5.78 shows an in-place object resulting from an extrusion. It is part of the window but it was modeled as an independent object with no parameters, which means that not only it will have to be edited one separately for each single similar window, but also that changes will be very limited. In case we want to replace windows, we will additionally have to replace sills one by one.

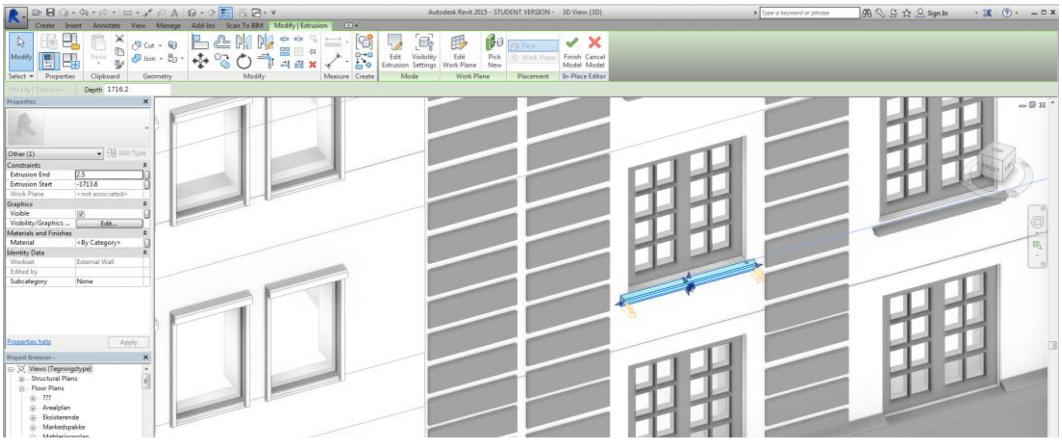


Figure 5.78- Non parametric object. Source: image courtesy Dark Arkitekts

Furthermore, Figure 5.79 shows a frame object that was modeled as a non-parametric family with independent extruded objects. As a result, limited changes can be made, because all elements of the family need to be edited one by one to keep the window object correct.

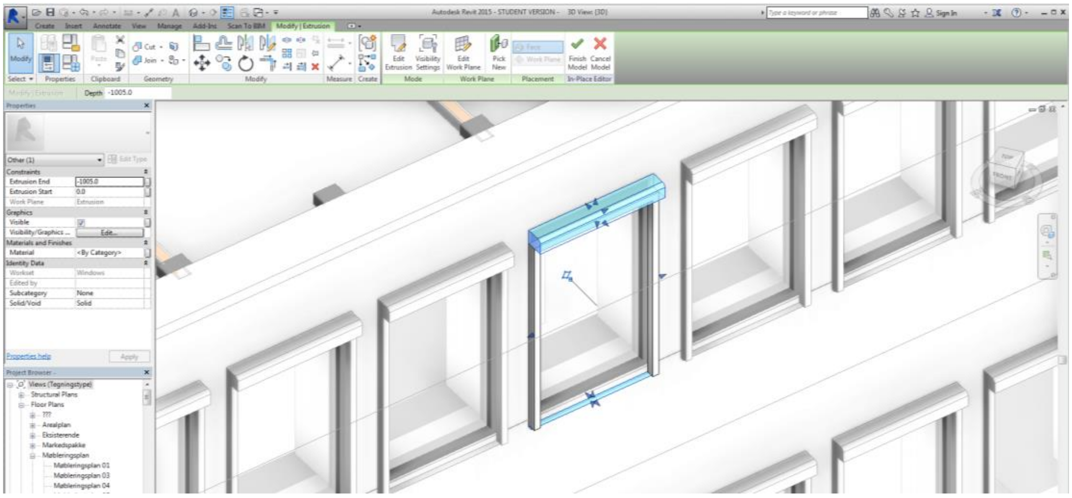


Figure 5.79- Non-parametric object frame. Source: image courtesy Dark Arkitekts

If these objects are parametric and with type parameters, the user can change one window and this change would apply to all of the same type. The element would be easily replicated and changed and schedules are easily generated, including an appropriate structure and list of geometric parameters.

This model did not have LOD or tolerances, and its modeling process was not coherent and some elements were not parametric.

When modeling begins, it is important to know the end user's goals. It is important to focus on the highest precision of the model, if it is to be used as documentation for a renovation. Alternatively, if the existing building is not going to be that intensively used, a quick and generic representation of the object suffices, allowing the user to spend time in the new parts that are not so related to the existing. Such model goals should result in discussions about what needs to be in the models regarding the LOD, Accuracy, Scope of work, and so forth.

C. Modeling through PCM workflow

Mosque of El Jebel Shrine | Denver, CO |The Beck Group

Project goal:

In this project, the goal was to refurbish the Mosque of El Jebel (Figure 5.80), while preserving its century old architectural style. The survey team members were Margarida Barbosa and Silviu Stoian. The modeling team members were Silviu Stoian and Ronnie Schmidt.

Figure 5.80- Mosque of El Jebel Shrine. Source:Google maps

This project needed a very detailed BIMs, with construction information whenever the scan data or field notes and photos captured structural and material details.

Acquiring and processing workflows:

Figure 5.81 shows the schematic diagram of the acquisition and processing workflows and the case study steps sequence, described in the next paragraphs.

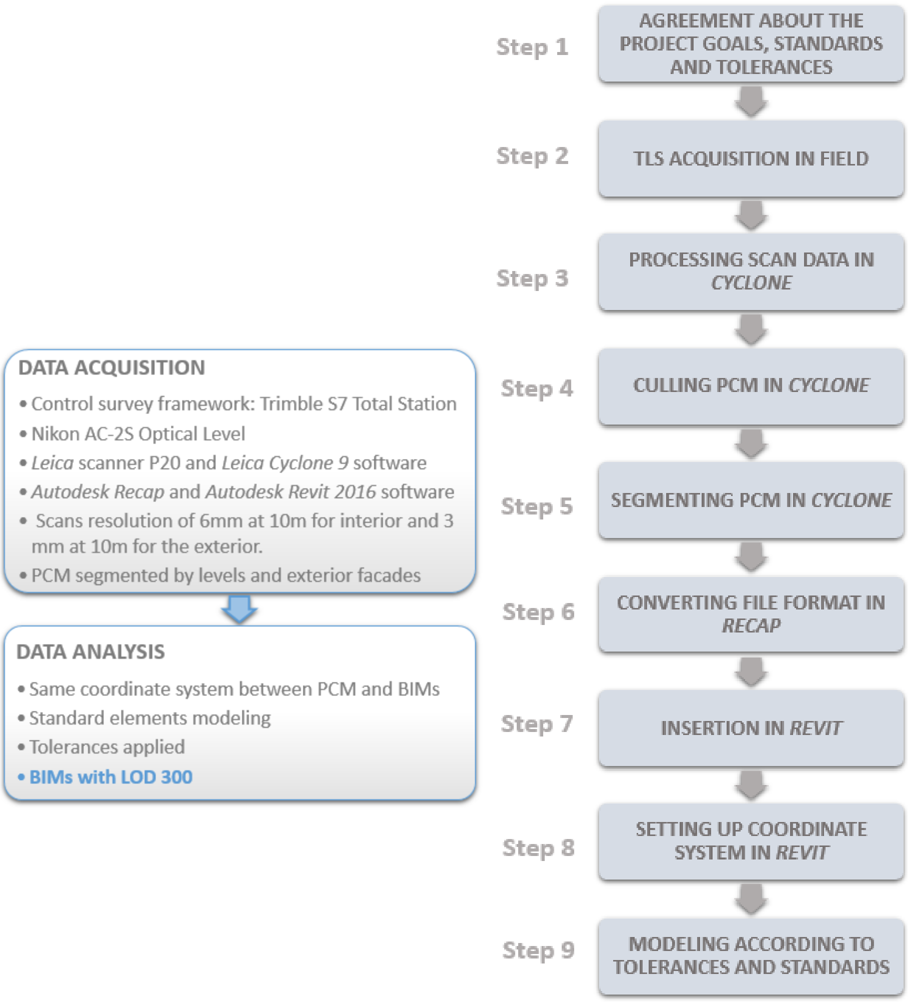


Figure 5.81- Schematic diagram of the acquisition and processing workflows and the case study steps sequence

A complete laser scanning survey, including the roof and the exterior, was done after the control network survey was fully established. The laser scanning team captured apparent geometry, and assessed and verified existing conditions that could not be recorded by surveying instruments. This kind of information, like type of materials, materials from interior layers of walls (visible due to holes), constructability methods, etc., was documented in field notes and photos (see Chapter 2 and Section 5.1).

The tool used for control survey was a Trimble S7 Total Station; for the TLS survey the team used a Leica ScanStation P20; and photos were acquired with a Nikon AC-2S Optical Level. Regarding processing software the team used *Leica Cyclone 9* and *Autodesk® Recap®*. Scans without color were captured at a resolution of 6.3 millimeters, at 10 meters from the scanner, for interior spaces, and 3.1 millimeters, at 10 meters from the scanner, for exterior spaces. The scan data was registered and oriented in *Cyclone*, where unwanted data from reflection and refraction was removed.

Modeling workflow:

After the scans registration process was completed, an as-built *Autodesk® Revit®* model was generated solely from point cloud data, that was the basis for design. The *Autodesk® Revit®* content was developed with LOD 300 (described in Section 4.2.2) and was adjusted to meet the agreed BIM Execution Plan and Standards (see Chapter 4). These standards were agreed in an initial project meeting, assuring consistent modeling procedures and methodology across the project. It was also critical to define a coordinate system that worked for the PCM and BIMs, in this case a local coordinate point was specified in the building. The modeling was done with *Autodesk® Revit® 2016.*

The most efficient way of managing point cloud models in *Autodesk® Revit®* is to subdivide the PCM into building areas like 1st level, 2nd level, basement, exterior and facades. One can load and unload point cloud files to visually confirm information. This option of removing some point cloud files decreases the *Autodesk® Revit®* file size, which results in a better software performance. The less powerful the machine is, the more important this step is. It is also easier for the user to control and analyse the information by parts. Figure 5.82 shows the segmented PCM file that contains the building facade data.

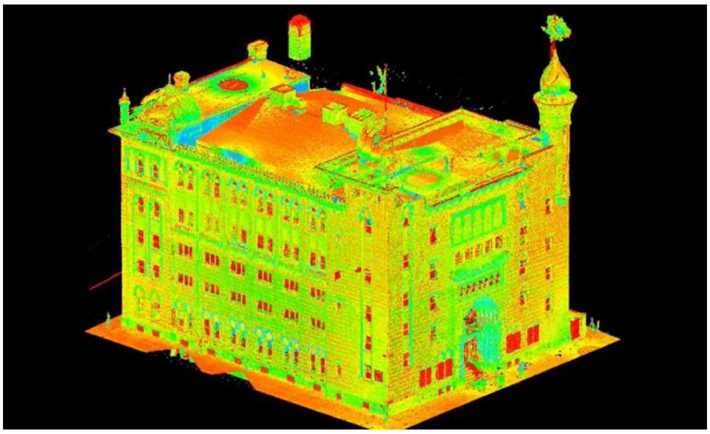


Figure 5.82- PCM segment area correspondent to the exterior. Source: image courtesy The Beck Group

It is extremely important that the origin of this segmented point clouds is not changed so they can relate to each other, and so they can connect with the *Autodesk® Revit®* 's origin when inserted. This leads to the first modeling step: setting up an *Autodesk® Revit®* file in order to link a PCM. The

Autodesk® Revit® file should have the same coordinate system as the PCM which results in a direct insertion of the linked files (Figure 5.83). It is necessary to establish a strategy that allows the same position in space for different kinds of information originating from several intervenients. A shared coordinate system allows an easier collaboration between different people, files and specialties, avoiding errors.

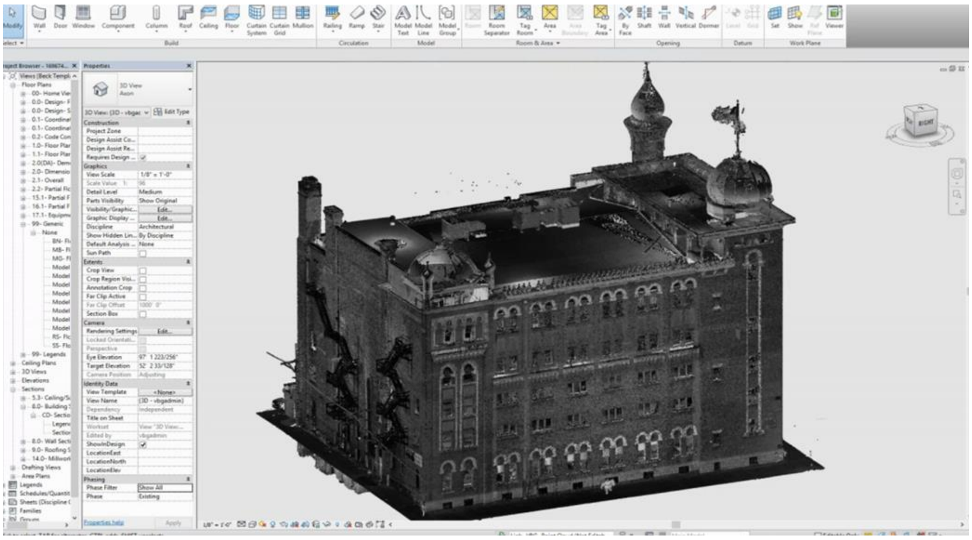


Figure 5.83- PCM directly inserted in *Autodesk® Revit®.* Source: image courtesy The Beck Group

To set up the *Autodesk® Revit®* file where the PCM was inserted, some guidelines were followed. We outline some main recommendations that can be easily adapted to any other similar BIM software.

1. **Creating the *Autodesk® Revit®* file:**

It is important that all people in the team work in the same *Autodesk® Revit®* version, which is defined in the beginning of the project.

The project organization was set up differentiating existing phase and new phase information in different groups. Existing elements should be connected to the existing phase, while new ones should be connected to the new phase group.

2. **Setting up the coordinate systems**

The PCM was inserted based upon the Shared Coordinate System. Since the PCM is in "real-world" coordinates, it may be hundreds to millions of meters in any direction. *Autodesk® Revit®* performs best when all modeled geometry is located in a close proximity to the relative origin, and this is why the project base point was redefined. The project base point can be understood as the origin of a "local coordinate system" for the building.

The PCM needed to be inserted to redefine the project base point. The project base point was a location in the building chosen by the team. Setting the project base point through an unknown coordinate:

- ❑ The location of the PCM was identified and it was defined where the project base point should be relocated.
- ❑ Once the corner was established, the team placed an annotation that reports the point coordinates in the model relative to the shared origin, the project origin, and the relative origin. These were the values for N/S and E/W.
- ❑ The elevation and rotation from true north was also needed to modify the project base point. The building was modeled with project north respecting the relative origin north, which means the model was not built with true north angles set in the project north orientation.

After the project base point, internal coordinate system, and the point cloud have been redefined and set, the modeling can begin. Different projects have distinct modelling approaches depending on the purpose of the model. The modeling goal was to represent the building as detailed as possible, with wall material description and geometry. This building had a very complex ornamented geometry, requiring specialized workers, several working hours and the interpretation of what should be simplified or what was essential to remain true to.

3. **Project modeling standards**

The modeling procedure followed some main guidelines:

- ❑ It was important to model the existing elements connected to existing phase group
- ❑ Before modeling, dimensions and tolerances were defined.
- ❑ Element measures were adjusted to the nearest 5 millimeter increments, with even measures;
- ❑ Elements were modeled within 5 millimeters from the PCM, where possible and sufficient data was available. Where surfaces of elements were irregular (field stone, brick, etc.), the elements were modeled within 10 millimeters from the PCM;
- ❑ Elements were modeled orthogonally (or with 45 degree angles and multiples) relative to the model origin, axis and reference planes;
- ❑ Elements that were intentionally built non-orthogonally should be adjusted to the nearest 0.01 degree;

- The as-built model was generated through the PCM by manually placing the dimensions as they appear. Reference planes were drawn orthogonally and within 5 millimeters tolerance from the origin, with even dimensions. Reference planes can be used to help creating tolerances and controlling elements position and measurements. This reduces dimensional inconsistencies that occur with the snap to point cloud modeling method.
- Where the tolerances were not possible, comments were associated with the elements and views.
- The project was developed with LOD 300, as agreed in the BIM Execution Plan, whenever this was not possible generic elements were used and noted.
- Standard element types (like walls and door) were used where possible.

Critical analysis of workflow and outputs

The field notes documentation workflows could be improved with the use of digital tools, replacing the use of several papers in site. To assist the survey one can use tools like tablets with apps like *Autodesk® BIM Field®*[36], where the scan map pdf, previously planned, is integrated with comments. This tool can be used to register additional site information, including the acquisition of photos and drawings.

The coordinate system used for the PCM and BIMs should be planned and specified prior to survey and communicated to the survey team. This allows the specific point defined in the building to be correctly acquired and documented.

The PCM provides the highest level of dimensional accuracy (relative to the *Autodesk® Revit®* model). The BIMs serves as the base design model for future intervention projects.

The final BIMs 3D section is shown in Figure 5.84, where we observe the complexity of existing elements and their relations.

[36] *https://info.bim360.autodesk.com/bim-360-field*

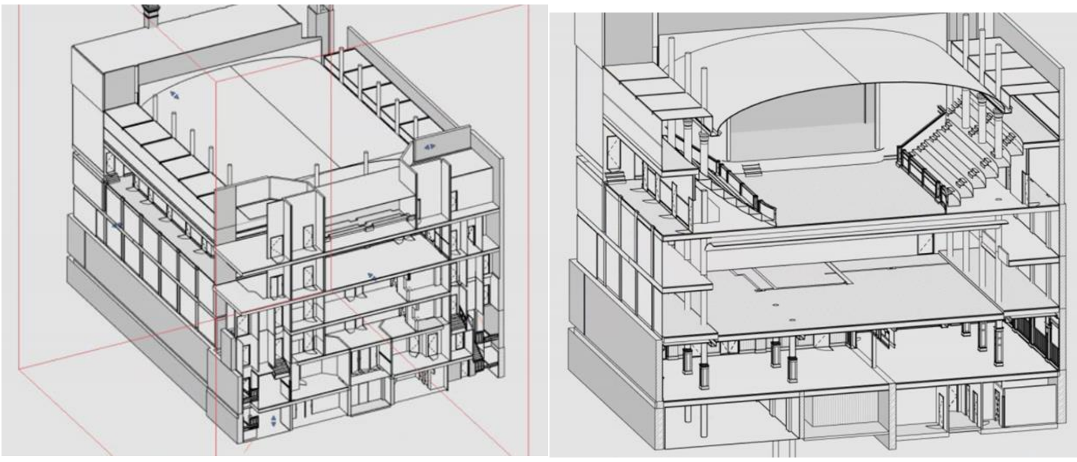


Figure 5.84- El Jebel Mosque BIMs. Source: image courtesy The Beck Group

The team relied solely on the data presented by the PCM, photos and field notes to develop the as-built BIMs. The building TLS survey and the *Autodesk® Revit®* content were developed and adjusted to meet the BIM Execution Plan and Standards agreed previous to the project. The existence of standard guideline documents inside a company allows different people to produce the same outcome. The BIMs is more consistent, allowing a more efficient information exchange, and reuse in future interventions. The companies who do not adopt this kind of documents risk having different team members modeling in a different way, which will result in a heterogeneous model. Such a model is difficult to reuse and the output will not have the same quality.

In this project, quality assurance/ quality control efforts to minimize error were done from start to finish, by the team members. The modeling procedures and methodology were consistent across the project. The resulting model was very detailed, with construction information whenever the scan data and field notes captured structural details. The high level of information in this BIMs was possible because the surveying team knew the project goal. As a result, during the survey the scanner was positioned to capture the interior layers of walls or structural details whenever it was possible.

Medica Sur | Mexico City, Mexico |The Beck Group

<u>Project goal:</u>

The project team wanted to attach a new skin to the existing facades since it was not possible to build more square meters on the site. For this purpose, a TLS survey was essential and the BIMs had to be built with a completely different strategy from the one described in “El Jebel” project. The most important information was the facade deviations and the BIMs should reflect that information. This results in a visually “non esthetic” BIMs, since walls were not vertically continuous but stepping out to respect tolerances to the point cloud wall representation. The surveying and modeling team members were Ronnie Smith and Margarida Barbosa. Figure 5.85 shows a google maps caption of the Medica Sur hospital exterior.

Figure 5.85 - Medica Sur hospital. Source: Google maps

<u>Acquiring and processing workflows:</u>

Figure 5.86 shows the schematic diagram of the acquisition and processing workflows and the case study steps sequence, described in the next paragraphs.

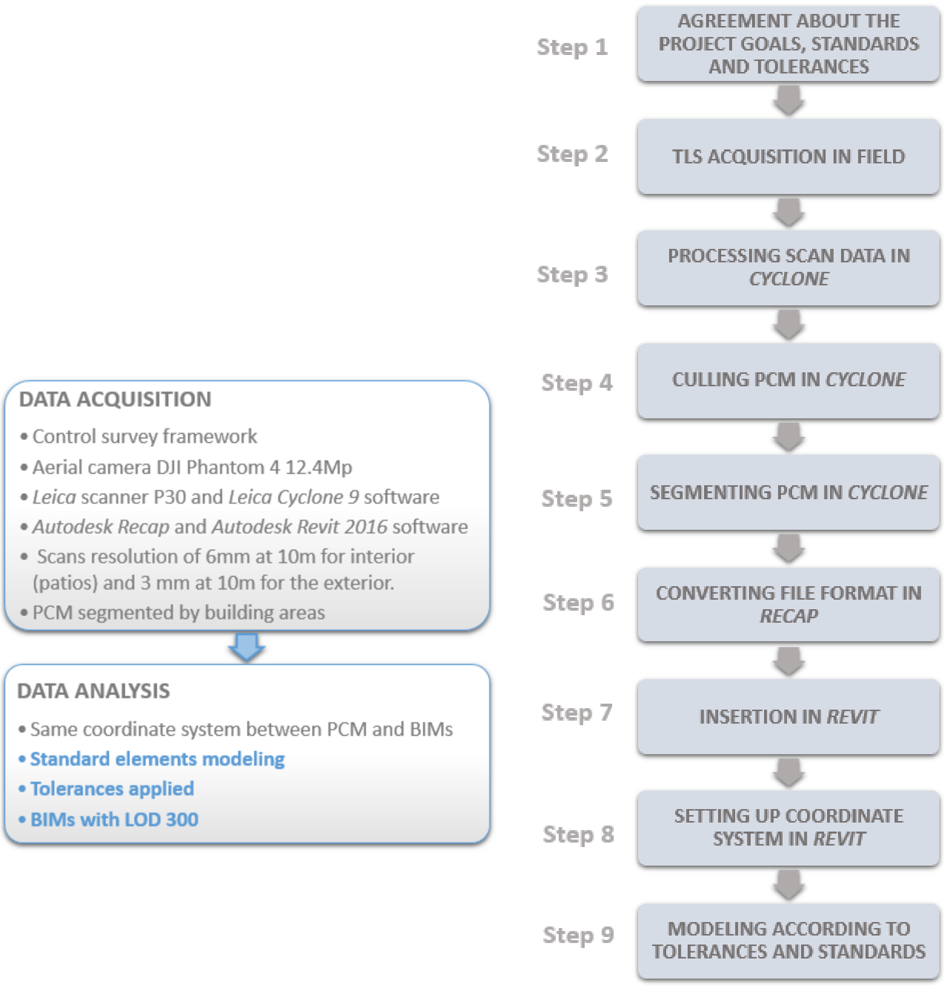


Figure 5.86- Schematic diagram of the acquisition and processing workflows and the case study steps sequence

A complete laser scanning survey, including the roof and the exterior, was done after the control network survey was fully established. The equipment and software that was used for TLS survey was a Leica Scanstation P30. Regarding processing software, the team used *Leica Cyclone 9* and *Autodesk® Recap®.*

Scans were captured at a resolution of 6.3 millimeters, at 10 meters from the scanner, for interior spaces (like patios) and 3.1 millimeters, at 10 meters from the scanner, for exterior spaces. During the survey it was observed that the pavement of some roofs moved when the team stand on them. This started interfering with the scans result, decreasing their quality and producing errors. This issue was solved with a remote control via mobile phone app (app like *Remote RDP Lite*[37]), connecting through WI-FI to the scanner. The remote control allowed the survey team to stand at a considerable distance from the pavement where the scanner was and start the scan.

The scan data was acquired without color and, posteriorly, registered and oriented in Leica Cyclone, where unwanted data from reflection and refraction was manually deleted. The PCM was segmented according to building areas as seen in Figure 5.87. Each color corresponds to a different point cloud file connected to a building area.

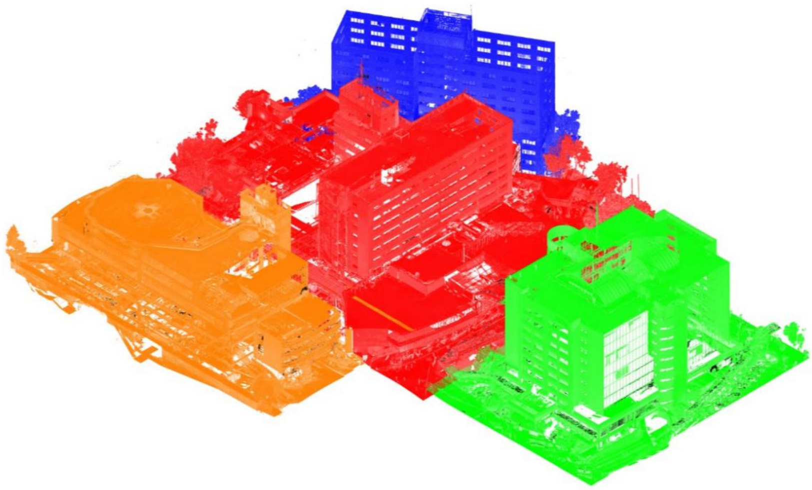


Figure 5.87 - PCM segmentation according to building area. Source: image courtesy The Beck Group

<u>Modeling workflow:</u>

[37] https://play.google.com/store/apps/details?id=org.toremote.rdpdemo

The modeling was done with Autodesk® Revit® 2016. The setup of *Autodesk® Revit®* file and insertion of the PCM into the file followed the same steps described in “El Jebel Mosque” project.

The first step was to determine a corner of the existing building to align with relative origin North, in order to model elements orthogonally. The model did not have True North angles set in the project North orientation. Tower 2 (green point cloud) was identified as the priority to start design development. For this reason, the origin for model was located at the ground floor of the southwest Tower 2 building corner.

During the modeling, drone images (acquired by Grant Hagen) were used whenever PCM information was lacking, which was sometimes an issue due the huge quantity of glass panels (Figure 5.88).

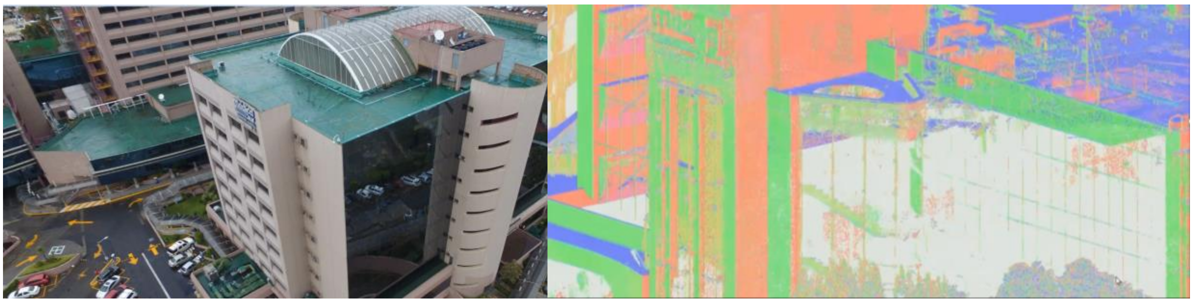


Figure 5.88-Drone images (left) were used to complement lack of point cloud information (point cloud on the right with blank area instead of points). Source: image courtesy The Beck Group

The PCM visualization option, inside *Autodesk® Revit®,* was set up according to the normals vector direction value color. This visualization option allows a better understanding of element directions and to differentiate the PCM from the parametric elements. Figure 5.89 shows how it is possible to easily identify the points corresponding to walls with different direction. Where one direction is represented by green points and the other by orange points, while the roof points representation is blue.

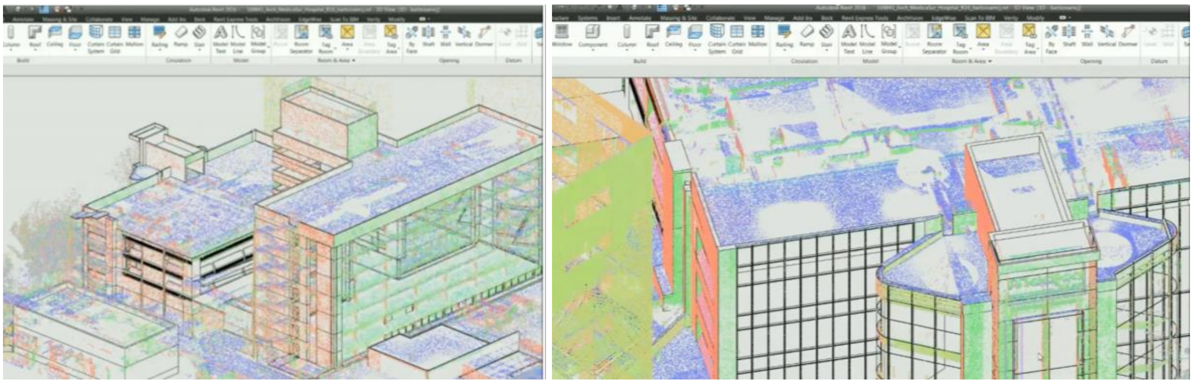
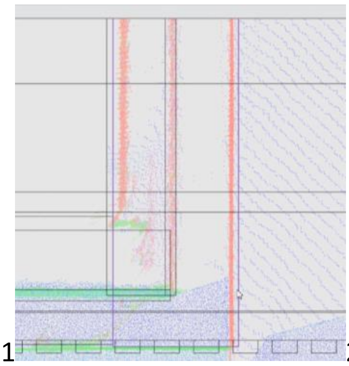


Figure 5.89- Images of the BIMs with the PCM colored by normal color values. Source: image courtesy The Beck Group

All elements were modeled in the existing phase and the goal was that their level of development was LOD 300 except when information was lacking, then no LOD was added (generic elements). The modeling process begun on Tower 2. Throughout the process of modeling as-built conditions the following rules were followed:

- ❑ Elements were modeled orthogonally (or with 45 degree angles and multiples) relative to the model origin, axis and reference planes;
- ❑ Elements that were intentionally built non-orthogonally were modeled to the nearest 0.01 degree;
- ❑ Elements were modeled within 5 millimeters from the PCM, where possible and sufficient data was available. Elements between columns (and associated grids) were stepped forward or backward according to PCM tolerances.
- ❑ Prior to elements modeling, reference planes were drawn orthogonally and within 5 mm tolerance from the origin, with even dimensions. Elements were measured from one face of the element (for example one side of the wall) to the reference planes. “Snap to Point Cloud” technique is not used since it hinders the use of tolerances, instead, manual input of measures modeling method was executed;
- ❑ Element positions resulted from the average of the furthest left points and furthest right points of the set of points representing the elements exterior face. This is illustrated in Figure 5.90, where from 1 to 2 we can observe the variation of the point cloud wall representation (in pink color) that goes from the left of the Autodesk® Revit® wall element to be on its right side.


1

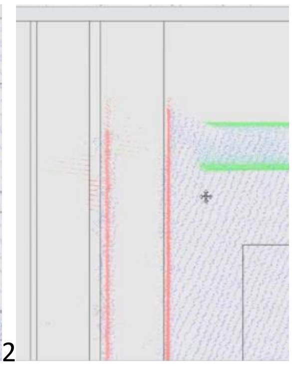

2

Figure 5.90- Image 1 shows the point cloud represented in pink in the left of the wall element; Image 2 shows the same point cloud and wall element but now we observe it is on the right r side of the wall element. Source: image courtesy The Beck Group

- ❑ Element measures were adjusted to the nearest 5 millimeters increments, with even measures;
- ❑ Where tolerances were not possible to respect, annotations in elements and views were done (Figure 5.91).

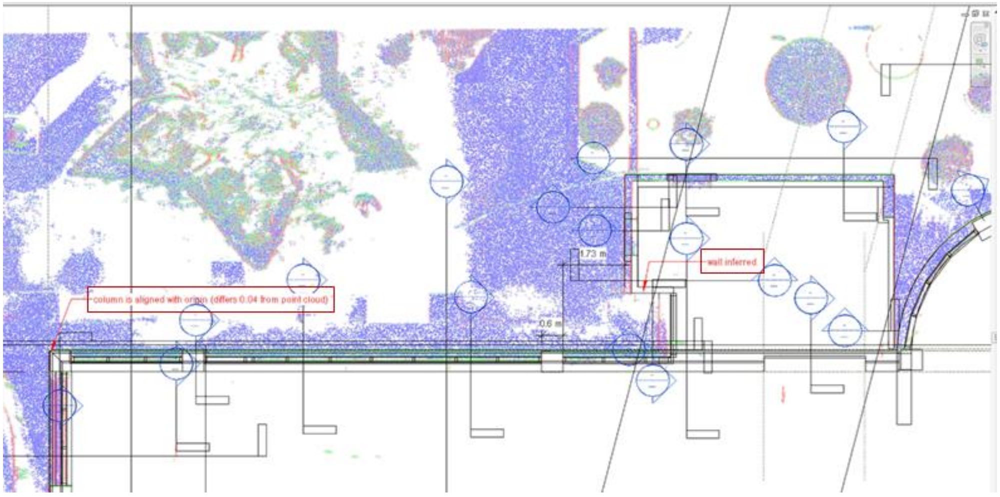


Figure 5.91 - Comment in red marking elements out of tolerance. Source: image courtesy The Beck Group

Sections were continuously made while modeling, so that the element tolerances could be checked horizontally and vertically.

Critical analysis of workflow and outputs

The PCM provided the highest level of dimensional accuracy (relative to the *Autodesk® Revit®* model). The parametric model served as the base design model for the facade refurbishment projects.

The modeling tolerances and standards described in this project were based on the company's internal documents provided to the modeling team, and contributed for a consistent and reliable BIMs.

Figure 5.92 shows the BIMs used by the architects to start planning the facade intervention. Only facade elements, slabs and roofs were modeled. The model is a direct result of the project goal: the intervention in the facades.

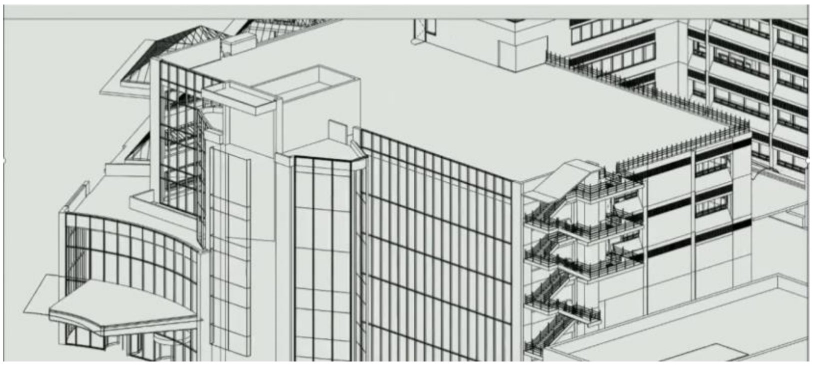


Figure 5.92- Medica Sur BIMs . Source: image courtesy The Beck Group

In this project it was very important that BIMs elements were in the vertical and horizontal average point of the corresponding point cloud element. For example the Autodesk® Revit® walls should be segmented by levels and centered with the average point of the PCM so that the tolerance would not increase. This is why it is a “non esthetic” BIMs: walls and facade elements are not vertically continuous but stepping out to respect tolerances to the point cloud wall representation. Figure 5.93 illustrates the vertical stepping, resulting from placing the wall in the average point.

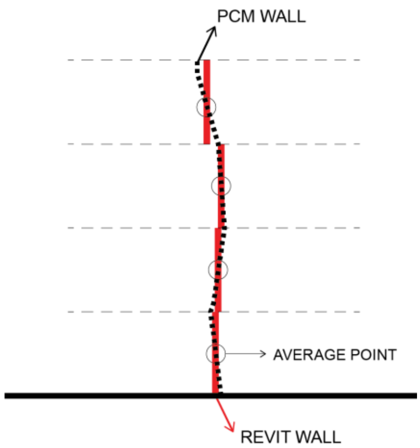


Figure 5.93- vertical wall stepping

College Station Theater|Houston, TX |The Beck Group

This project was already documented in Section 5.1.2, where we saw how the 360° panorama photos were used to complement missing information for modeling. In this Section, we will focus on the modeling workflow for the BIMs generation, outlining steps that could become guidelines to handle the high modeling effort.

Project goal:

This project was a refurbishment of a cinema building (Figure 5.94). The idea was to change minor elements, not to intervene profoundly on the building. This project did not aim at a fully detailed representation of reality, but rather at a simplified version. Essential was the process speed and efficiency in *Autodesk® Revit®* software, while respecting the agreed standards. The surveying team members were Ronnie Smith and Margarida Barbosa. The modeling team members were Ronnie Smith, Margarida Barbosa, Micah Gray and Brendan Nichols.

Figure 5.94 - College Station Theater. Source: Google maps.

Acquiring and processing workflows:

Figure 5.95 shows the schematic diagram of the survey and data analysis workflows described in the next paragraphs.

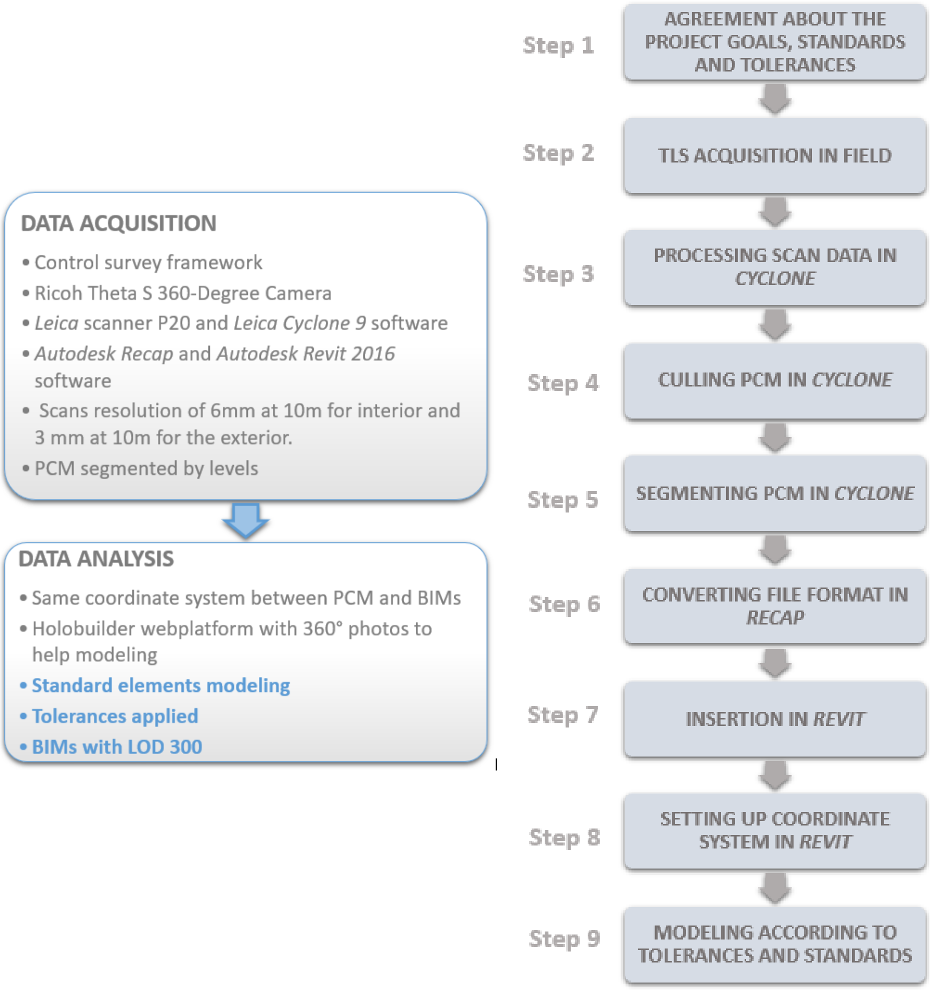


Figure 5.95- Schematic diagram of the acquisition and processing workflows and the case study steps sequence

A complete laser scanning survey of the interior (Figure 5.96) was done after the control network survey was fully established. Exterior scans were captured when needed to connect the interior. The equipment and software that was used for TLS was a Leica Scanstation P20.

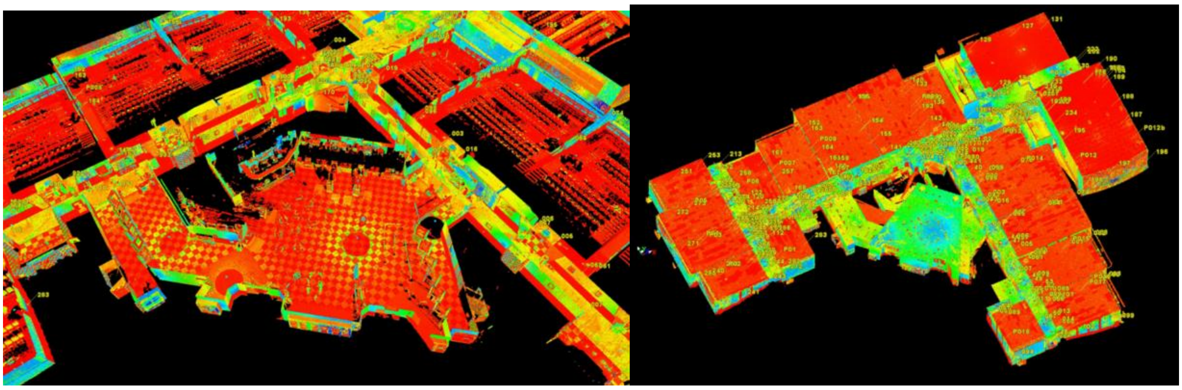


Figure 5.96 - "College Station Theater" project interior TLS survey. Source: image courtesy The Beck Group

The field notes documentation were registered through an Ipad in the *Autodesk® BIM Field®* app, using a scan map, previously planned, to add comments. This tool was used to register additional site information, including the acquisition of photos.

Regarding processing software, the team used *Leica Cyclone 9* and *Autodesk® Recap®*. Scans were captured, without color, at a resolution of 6.3 millimeter at 10 meters from the scanner for interior spaces and 3.1 millimeter at 10 meters from the scanner for the exterior spaces, whenever needed. The scans were registered and oriented in *Cyclone*, where unwanted data from reflection and refraction was manually removed. The PCM was segmented according to the building levels.

Posteriorly to the described survey, the project team visited the building with a 360° camera and acquired specific building areas. These photos were inserted in the Holobuilder webplatform and linked with CAD drawings.

Modeling workflow:

The modeling team of this project were three people, including myself. The modeling was done with *Autodesk® Revit® 2016*. The setup of the *Autodesk® Revit®* file and insertion of the PCM into the file followed the same guidelines described in "El Jebel Mosque" project.

The team determined a corner of the existing building to align with relative origin North, in order to model elements orthogonally. The model did not have True North angles set in the project North orientation.

Once the team had everything set, the modeling from the PCM was according to the following directives:

- ❑ Elements were modeled in the existing phase group;
- ❑ Elements were modeled orthogonally (or with 45 degree angles and multiples) relative to the model origin, axis and reference planes;
- ❑ Elements that were intentionally built non-orthogonally should be adjusted to the nearest 0.01 degree;
- ❑ Elements measures were adjusted to the nearest 5 millimeters increments, with even measures;
- ❑ Elements were modeled predominantly within 5 millimeters from the PCM, where possible and sufficient data was available;
- ❑ Where the tolerances were not possible, comments were associated with the elements indicating the deviation and reason for it;
- ❑ Prior to element modeling, reference planes were drawn orthogonally and within 5 millimeters tolerance from the origin, with even dimensions measured from one face of the element (for example one side of the wall). The "Snap to Point Cloud" technique is not used since it hinders the use of tolerances; instead, a manual input of measures was done;

- ❑ Elements were modeled with the LOD 300; whenever this was not possible, annotations were made in the element or view.

The Holobuilder 360° photos (Figure 5.97), used as described in Section 5.1.2., helped modeling when the point cloud data was not enough. This was a valuable tool to understand building materials and some missing data from the PCM.

Figure 5.97- Holobuilder 360° photos web platform as a tool for helping modeling. Source: image courtesy The Beck Group

Critical analysis of workflow and outputs

The field notes documentation in a digital workflow enhances the use of metadata while processing the data and also while modeling. The papers or notebook used during the survey often become too dirty or disappear. They are also not user friendly to carry around additional to the camera and the laser transportation. The use of a tablet to acquire photos and take notes, which can be saved in the cloud and connected to the project database improves the field survey workflow. It also simplifies the access and management of the metadata storage.

To provide a simple and clear basis for the design project, it was important to model the elements with even dimensions and to adjust tolerances to the nearest 5 millimeters increments. The PCM visualization option was according to PCM vector normals color, which allowed to distinguish in an easier way the different point cloud elements as we can observe in Figure 5.98, with green, pink and purple colors.

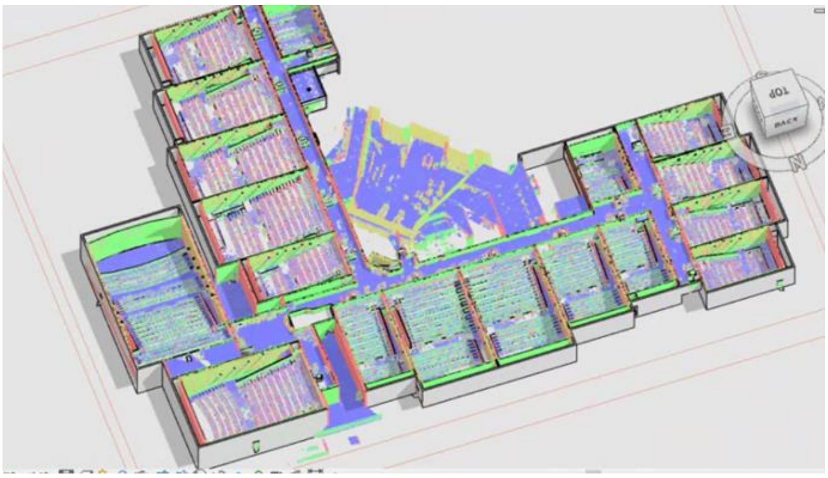


Figure 5.98- BIMs integrated with PCM. Source: image courtesy The Beck Group

The use of reference planes to control dimensions enhanced the standardized and consistent modeling process. This was evidenced in the QA/QC of the auditoriums, where dimension and position of risers, walls, floors and lighting fixtures were checked. The BIMs (Figure 5.99) was modeled without much detail information about constructive elements and with simplified elements.

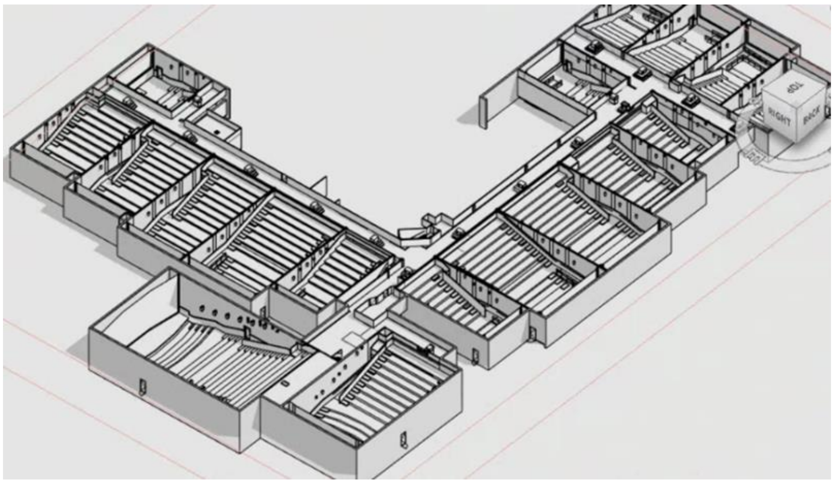


Figure 5.99-"College Station Theater" project BIMs. Source: image courtesy The Beck Group

The PCM provides the highest level of dimensional accuracy (relative to the *Autodesk® Revit®* model). The parametric model served as the base design model for the refurbishment project.

5.2.2. Combining automatic and manual techniques for workflow efficiency

After addressing the handling and modeling of uncertain data and, the interpretation and selection of building information essential for the model creation issues; the automation of building data capture into semantic BIM objects and the automation of repetitive tasks are the next challenge to overcome the high modeling effort. Indeed, Volk et al (2014) outlines automation as one of the major research challenges for reducing the effort of capturing, processing, recognizing and as-built BIM generation.

Developments have been made for introducing automation and improving the current process of converting unstructured point clouds into BIMs elements. Semi-automatic geometric modeling software typically includes tools for directly fitting geometric primitives (planes, cylinders, spheres) to the 3D data. These tools are semi-automated and require significant user input thanks to the fact that idealized geometries are rarely seen in real facilities: walls are not exactly planar and corners are rarely precisely 90 °C.

A. Software for semi automatically model parametric elements

There are several plug-ins available to automate the shape recognition from a point cloud. We will focus here on those that connect with *Autodesk® Revit®*. We would like to reinforce that BIM is not *Autodesk® Revit®.* Yet*,* it is the software used for the case studies and in which this thesis research was done. Having this in mind, the next paragraphs describe *CloudWorx* for *Autodesk® Revit®* (Leica's plugin), *Scan to BIM* (Imaginit's plugin) and *Edgewise Building* (Clearedge software), as they are representative of most of the tools on the market.

Scan to BIM

Scan to BIM's toolset is mostly focused on the elements modeling and QA/QC. Its tools focus on improving the working process with point clouds in *Autodesk® Revit®*. They manage point cloud visualization; generate objects in *Autodesk® Revit®* based on the loaded points, for example architectural building elements (like walls, columns), toposurfaces and pipes among others; and analyze elements: adding measurements, performing deviation analysis to see how closely the object matches the point cloud, and interference checking (checking the point cloud against new objects). This tool also allows to adjust a slab to match deviation points from that slab's face, after the deviation analysis.

CloudWorx for Autodesk® Revit®

Leica's toolset for *Autodesk® Revit®* is similar to scan to BIM. The bigger difference is that it changes the way *Autodesk® Revit*® imports and displays points replacing them with their own point cloud engine. This changes the format inserted in *Autodesk® Revit®*. It uses the .imp format, proprietary format from Cyclone (Leica's stand-alone application), instead of .rcp/.rcs. The whole project database is used and not just an exported file. It also changes how the import/color/and limit point display. Point coloration is one of the most important tools to help end users understand what they are seeing and make the right decisions.

***EdgeWise Building* Modeling software**

EdgeWise Building software, from ClearEdge3D, semi-automatically identifies and extracts walls, windows, doors and other features from point clouds and exports them as *Autodesk® Revit®* family objects. Once in *Autodesk® Revit®*, the *EdgeWise* plugin has options to refit walls either "as-design" or "as-built" conditions. The following EdgeWise Building case study was provided by ClearEdge3D: Large National Bank headquarters and branch office building modeling. This was a 2787m^2 building with an interior highly compartmentalized; Figure 5.100 shows the interior of the building with scan positions included and marked by blue circles. The deliverables were a BIMs in *Autodesk® Revit®* and a 3D model in *SketchUp.*

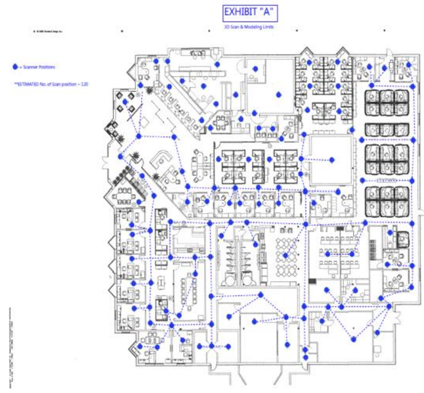


Figure 5.100- Bank Floor plan. Source: image courtesy ClearEdge3D

The modeling was done in *EdgeWise*, where walls were extracted (Figure 5.101, left image) and exported to *Autodesk® Revit®* (Figure 5.101, right image). These walls were simplified to be orthogonal, and were obtained in 1 day.

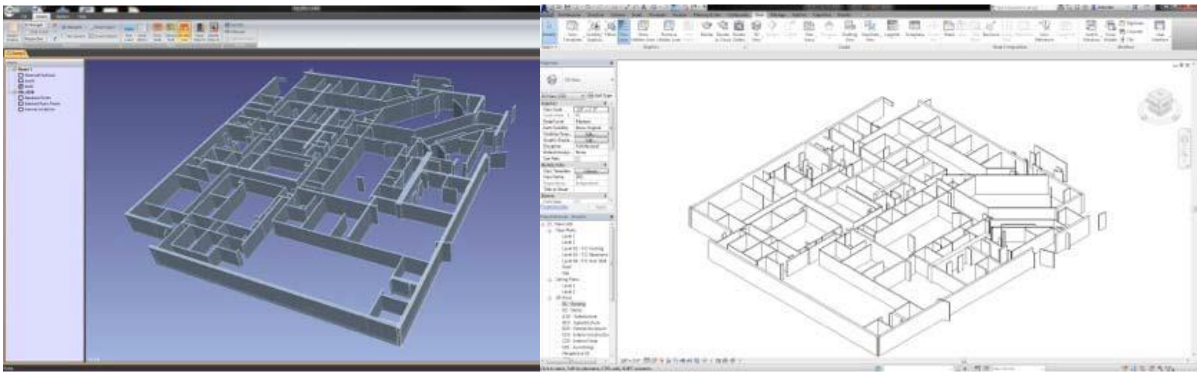


Figure 5.101- Image on the left:Walls extract in *EdgeWise Building;* Image on the right: wall imported into *Autodesk® Revit®* . Source: image courtesy ClearEdge3D

The manual walls tracing workflow took three days while *EdgeWise* Workflow took one day. In terms of efficiency *EdgeWise* saved 16 man-hours of modeling.

This type of tools can work with small projects, but each element needs to be checked since sometimes the algorithm recognizes walls where there are columns or other orthogonal elements. The PCM also has to be very clean and prepared so it does not confuse the software. In bigger projects, this checking and possible corrections will take some time and it may thus be more efficient to manually do it. It may not even be an option in non-orthogonal buildings or in projects where the representation has to be as close to reality as possible. These tools are a start and have definitely potential, but its use is defined by the project characteristics.

B. Visual programming extensions for repetitive tasks automation

Not only the automatic recognition of shapes through a PCM is relevant to improve the modeling workflow. Automation of daily modeling tasks and file set ups also enhances the speed and efficiency of modeling workflows.

Visual programming extensions, like *Grasshopper* and *Dynamo*, increase the efficiency of workflows. These tools are usually associated with the development of complex shapes. Nonetheless, one of their key strengths relies in the automation of repetitive tasks. These tools extend the basic software capacity enabling the user to visually create their own scripts according to specific needs of the project. It is more and more important to not use software without understanding or customizing it, transforming it according to projects needs instead of limiting to a general software usage.

Computational design is usually approached by dividing the problem into smaller problems or procedures to solve it. A step-by-step sequence of processes to solve the problem can be referred to as a definition, script or an algorithm. This sequence is normally subdivided into inputs that feed the instructions script, that generates an output (Figure 5.102).

Figure 5.102- Sequence of an algorithm.

Visual scripting was introduced for non-programmers to do what programmers do; therefore, designers are able to design their own tools to be used in their design process. I'm focusing on *Dynamo* and its expansion of the functionality of *Autodesk® Revit®* to outline how tasks, that can take some time to do manually, can be automatized through scripts. The choice of *Dynamo* examples is related to my use of *Autodesk® Revit®* and need to develop tools that will increase the speed of modeling and allow different analysis. Examples can be the generation of worksets when creating projects, duplicating sheets with views included, and clean/purge the *Autodesk® Revit®* file, among others. These are common tasks between projects that are repeated.

A. Create worksets when creating a projects

This script is important for collaboration efficiency, when several users are working on the same project. If multiple users want to work on an *Autodesk® Revit®* file, worksharing needs to be enabled. Enabling worksharing means that worksets will be created and that the Autodesk® Revit® file will become a central model after saved. Users will then need to create a local computer file to work on the project, and every time they synchronize their local file, work will be saved to the central file. At the same time, what other users did in the meanwhile, that was also saved to the central file, will be received in the local user file. Worksets are a named collection of related elements containing model elements.

The user can place the PCM in its own workset, which adds control and additional visual and project stability support. When opening the BIMs file, the user can specify what worksets should be open/closed. PCM files can delay the opening speed of a file, therefore if the workset that contains it is closed, it will increase software performance.

One can create an *excel sheet* with the names of the desired worksets and import that list into Dynamo. From this list, dynamo creates worksets in Autodesk® Revit®. Figure 5.103 shows the dynamo script with this process steps.

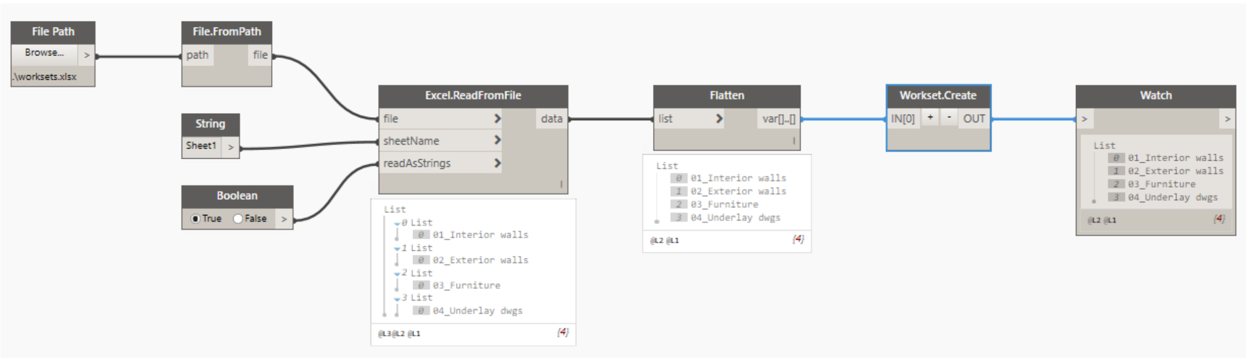


Figure 5.103- dynamo script to Create worksets

If the user applies the same established worksets in every project, the time spent building the script is saved after the first project.

B. Duplicating sheets with views included

It is not possible to duplicate a sheet with views in Autodesk® Revit® and sometimes the same sheet layout is repeated several times, like the floor plan sheets. Duplicating sheets and views can be a repetitive, laborious task, for example for buildings with several levels. Such a task can be replaced by a Dynamo script (Figure 5.104).

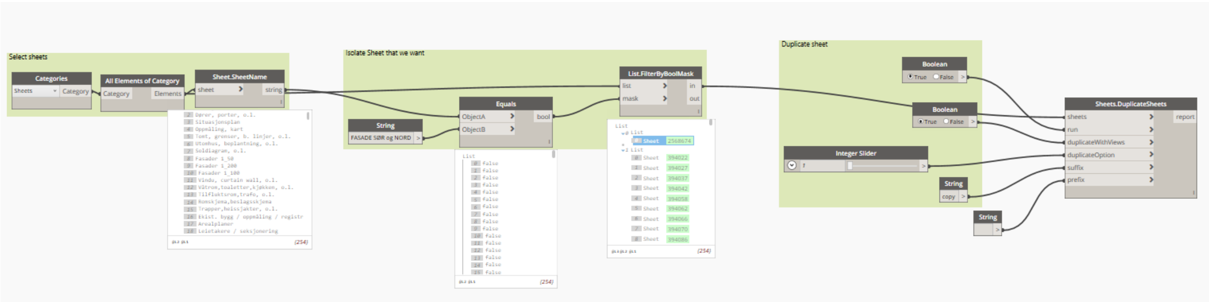


Figure 5.104- Dynamo script for duplicating sheets with views.

Dynamo is able to select the sheet category, and isolate the desired sheet with the associated views. Figure 5.105 is subdivided in A, B and C so we can zoom in the steps of the Dynamo script.

Figure 5.105 - Zoom of the Dynamo script steps to duplicate sheet with views, A. contains the first part of the script and B. the second part

C. Clean/purge the *Autodesk® Revit®* file

Another example of how dynamo can automate repetitive tasks can be the script that allows the user to clean the *Autodesk® Revit®* file. This is useful for collaboration workflow efficiency, when one wants to send a file but it includes information not relevant to the receiver. The *Dynamo* script selects the non-desired elements like view sections or 3D views, and deletes them in Autodesk® Revit®. This is normally done in a copied file of the original *Autodesk® Revit®* file. Figure 5.106 shows the steps of this script in *Dynamo*. This script avoids the user to go element by element and delete them.

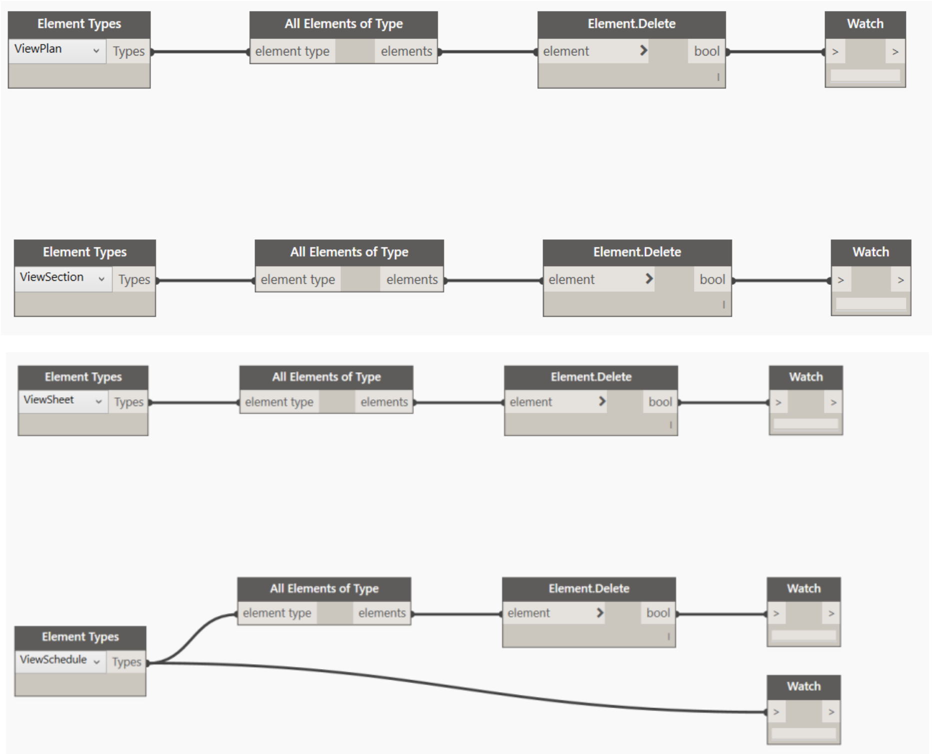


Figure 5.106 -Clean/purge *Autodesk® Revit®* file Dynamo script

These are some examples on how automation can speed and contribute to modeling or managing BIMs. One can find endless tasks that can be automated and vary from project to project.

C. Visual programming extensions for data analysis automation

Visual programming extension tools can be used to analyse building data and support project intervention decisions. An example is the solar study the Beck Group team (Virtual Building Group) was asked to develop. The reflection of the sun in the windows of a building was burning the neighbors building roof grass terrace, in distinct linear patterns across its surface. The team was tasked with both determining the cause of the melting and extrapolate the extents of the problem. The study was developed by Brendan Nichols and Micah Gray, that scanned and modeled the facade and roof in *Autodesk® Revit®*. The solar study, and consequent window sun reflection on the roof, was done through *Dynamo*. Converging sun reflections, throughout various times in the year, from windows with various sizes, were drawn in lines and the point where they intersect the roof was marked by a dot (Figure 5.107).

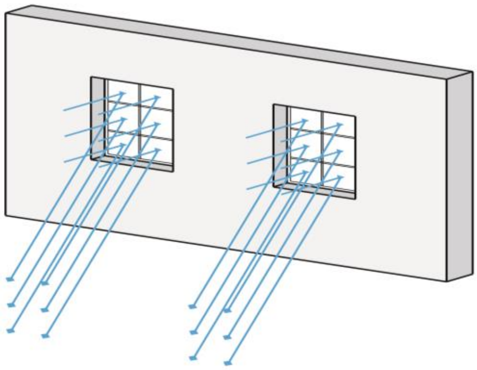


Figure 5.107 - Converging window sun reflections lines with the point where they intersect the roof

The team simulated the sun's path until the same converging angles were obtained as with the scan data, which showed the burn marks captured by TLS. Through a *Dynamo* script and the existing data of the burned path, the team simulated the overlapping areas for each set of windows and could predict where the reflection path would continue. This study allowed architects to find a built solution that prevented determined sun angles on the windows, and consequently stopped the burning grass marks.

5.3. Monitoring as-built information as a first step for the update and maintenance of information in BIM

This section describes several processes of monitoring buildings, specially during the construction phase. The case studies may also consist in new construction projects but they are set as examples of what can be applied for as-built BIM processes. It is valuable to have documentation describing the construction process associated with the BIM databases so that it is easier to intervene in the future for maintenance. The monitoring of a building detects deviations from what is considered the acceptable condition of an element, allowing to plan minor prevention interventions whenever needed. This section intends to describe processes of capturing building data that can contribute to updating the BIMs.

One can record a site construction evolution through drone photos. This is very useful for new constructions, but it can also be applied to the monitoring of existing building additions. It can document their construction process but also allow to understand how building parts connect and interfere in time, with visual proofs. Figure 5.108 contains a sequence of photos, acquired by Grant Hagen every two weeks, where we observe the evolution of a site construction. More specifically, the development of the building foundations on the left area of the site can be observed from image A to C.

Figure 5.108 - We observe the same site drone pictures with two weeks of difference from A to C. Source: image courtesy The Beck Group

This is how The Beck Group started monitoring their construction projects and merging this data with 4D schedules. Reports were prepared that included visual confirmations of the 4D schedules or justifications why they were not followed.

The images were introduced in a web platform "Skycatch" [38] and associated with a calendar. Every two weeks, new pictures were inserted in Skycatch and associated with the correct day. In addition, pdfs can be added and merged with the image data. This allows to understand whether the elements are being constructed according to plans. Figure 5.109 shows a top image where columns are marked with

[38] https://www.skycatch.com/

a red rectangle and a bottom image, with the same image with a pdf overlaid. There we can see that the column position has a correspondence between the site and the plan.

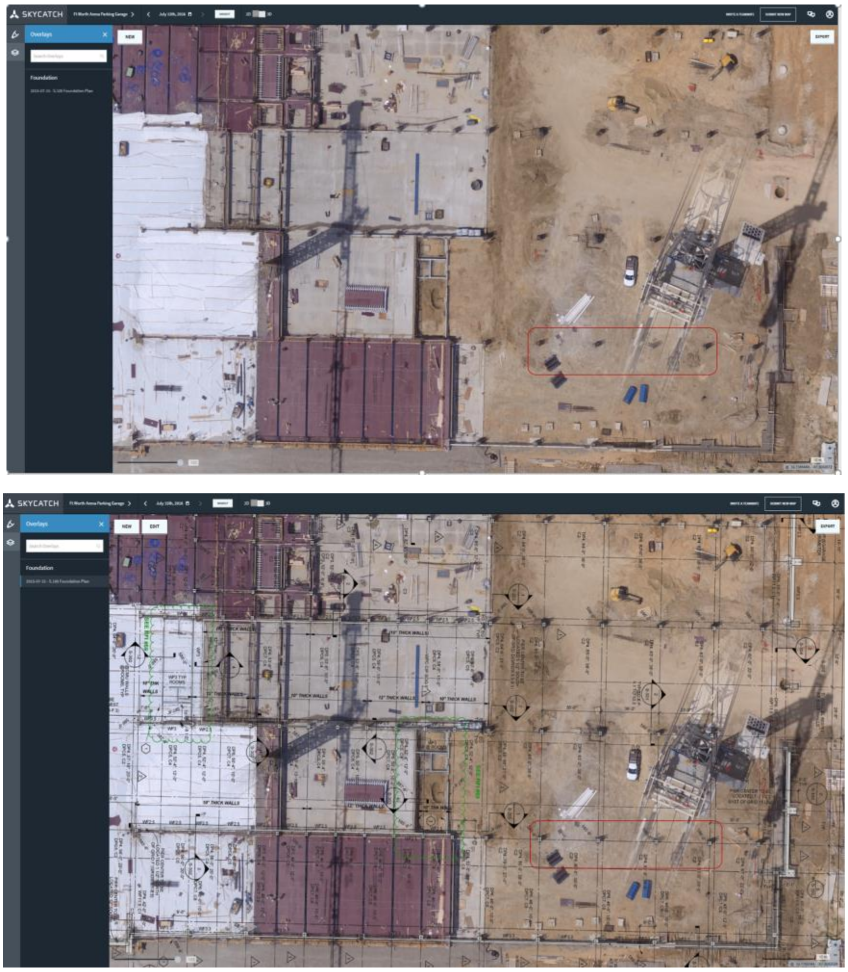


Figure 5.109 - We observe the same image. On top alone; in the bottom with pdf structural plan overlaid. Source: image courtesy The Beck Group

Throughout the building intervention development or the building life one can generate photogrammetric point clouds to monitor the building evolution. Not only the ADP PCM is an important tool to document the construction process but also the photos taken to generate are a valuable source of information (Figure 5.110).

Figure 5.110 - Photos detailing an intervention area of a building, used for ADP. Source: image courtesy The Beck Group

ADP PCM can be added to a previous point cloud survey or to a BIMs, adding information that will be valuable in the future either as a historic documentation or a monitoring data. Figure 5.111 shows a photogrammetric point cloud referring to a project refurbishment which intended to only preserve the structure of the building. This point cloud was added to a previous TLS survey to document what was being demolished.

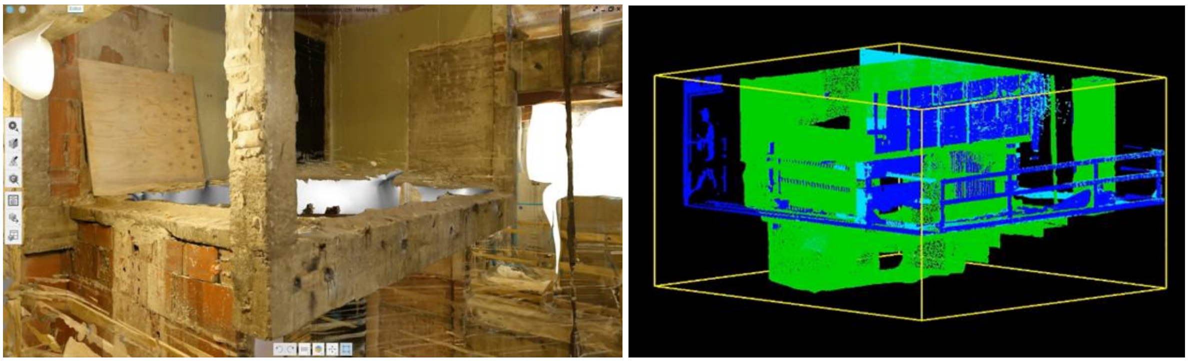


Figure 5.111 - ADP point cloud. Source: image courtesy The Beck Group

Figure 5.112 shows the ADP and the TLS point clouds merged. The ADP point cloud is seen in green and the TLS point cloud in blue. The ADP point cloud was inserted in *Leica Cyclone* software (after being scaled based on the TLS measurements) where the TLS was registered and oriented, assuming its orientation.

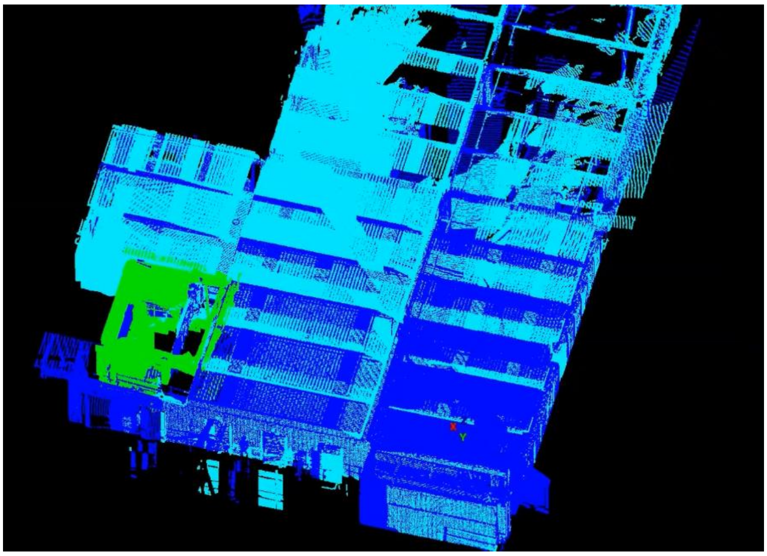


Figure 5.112- ADP point cloud (green) merged with TLS point clouds (blue). Source: image courtesy The Beck Group

Another way of monitoring building intervention progress can be through 360° photos inserted in the *Holobuilder*, where they can be associated with the plans they refer to. This can be done every two weeks, for example, to track the intervention evolution and provide documentation of the process for future interventions. They also allow the knowledge of where the hidden infrastructures are located and what are the inner layers materials of walls without having to open holes in the building to track them. Figure 5.113 shows a 360° photo example of a building in construction phase, where we can observe the ceiling infrastructure before being covered.

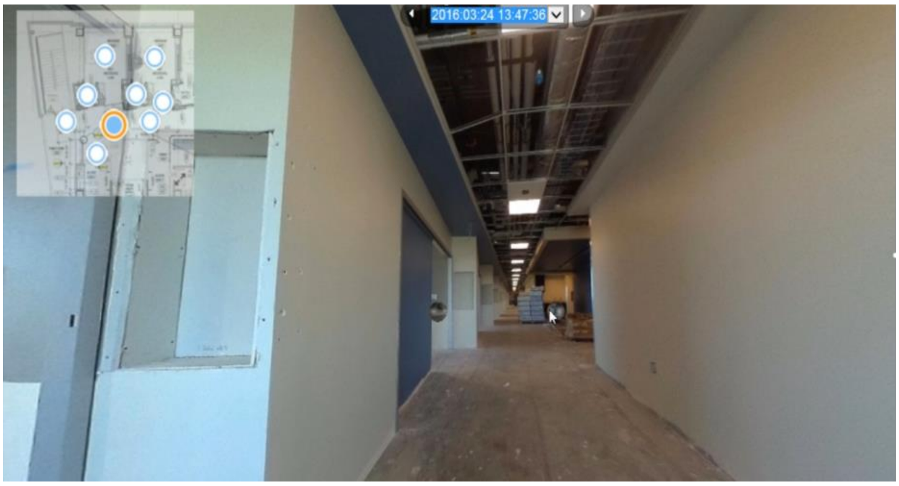


Figure 5.113- 360 image of construction phase. Source: image courtesy The Beck Group

Checking construction quality and consequent human comfort in the building can be done through data sensors. Data sensors (example in Figure 5.114) can capture different kinds of data like quantity of light, temperature, humidity and noise.

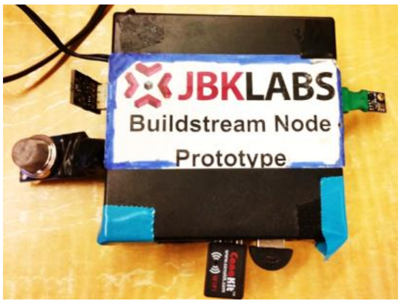


Figure 5.114- Sensor node installed at The Beck Group to test the building comfort.Source: image courtesy The Beck Group

At the Beck Group, it was decided to test how these sensors behave and collect data. Three sensor nodes (small electronic devices containing sensors) were located in different rooms. Figure 5.115 shows the location of two of them (black arrows).

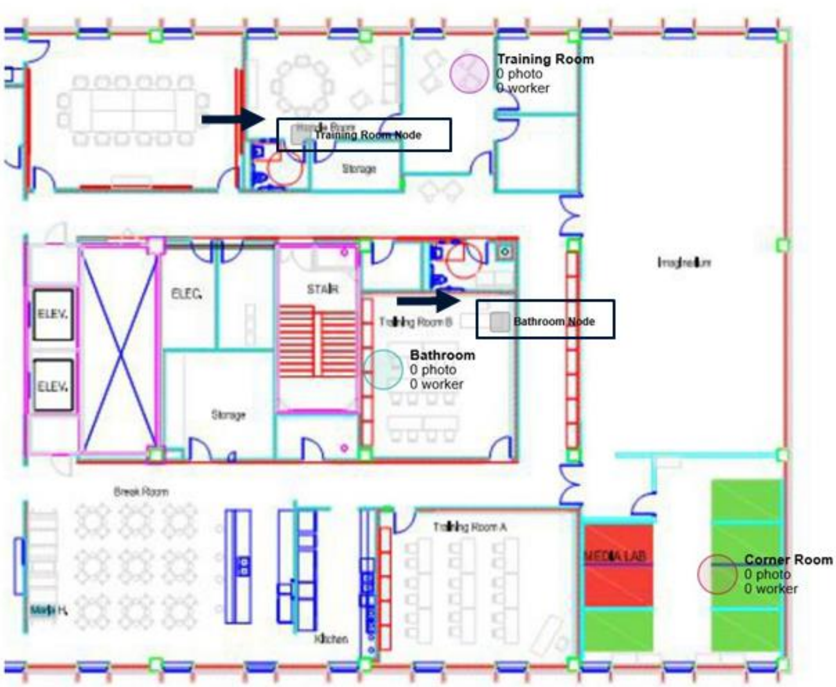


Figure 5.115- Plan map where the sensor nodes were located (we can observe two of the three installed).Source: image courtesy The Beck Group

The sensor nodes were located in the training room, in the conference room and in the bathroom. The data collected from the nodes installed in the different rooms was streamed to a common platform, which processed and generated graphic information. These graphics are connected with a calendar and the room which they refer to for analysis. From the data collected by the node sensors, I focus on the light, temperature, and humidity. Figure 5.116 shows their graphics: the data corresponding to the training room is represented in green, the conference room data in red, and the bathroom data in yellow. This data was recorded during 28 days in September 2015. We can observe that temperature is in Fahrenheit and varies between approximately 73F (23°C) and 84F (29°C). The bathroom has the biggest temperature differences. All the room temperatures vary in a similar way. In the humidity graphic we can observe that the bathroom is not always the most humid place. The training room can become quite humid. The conference room had a low humidity period on september 14th.

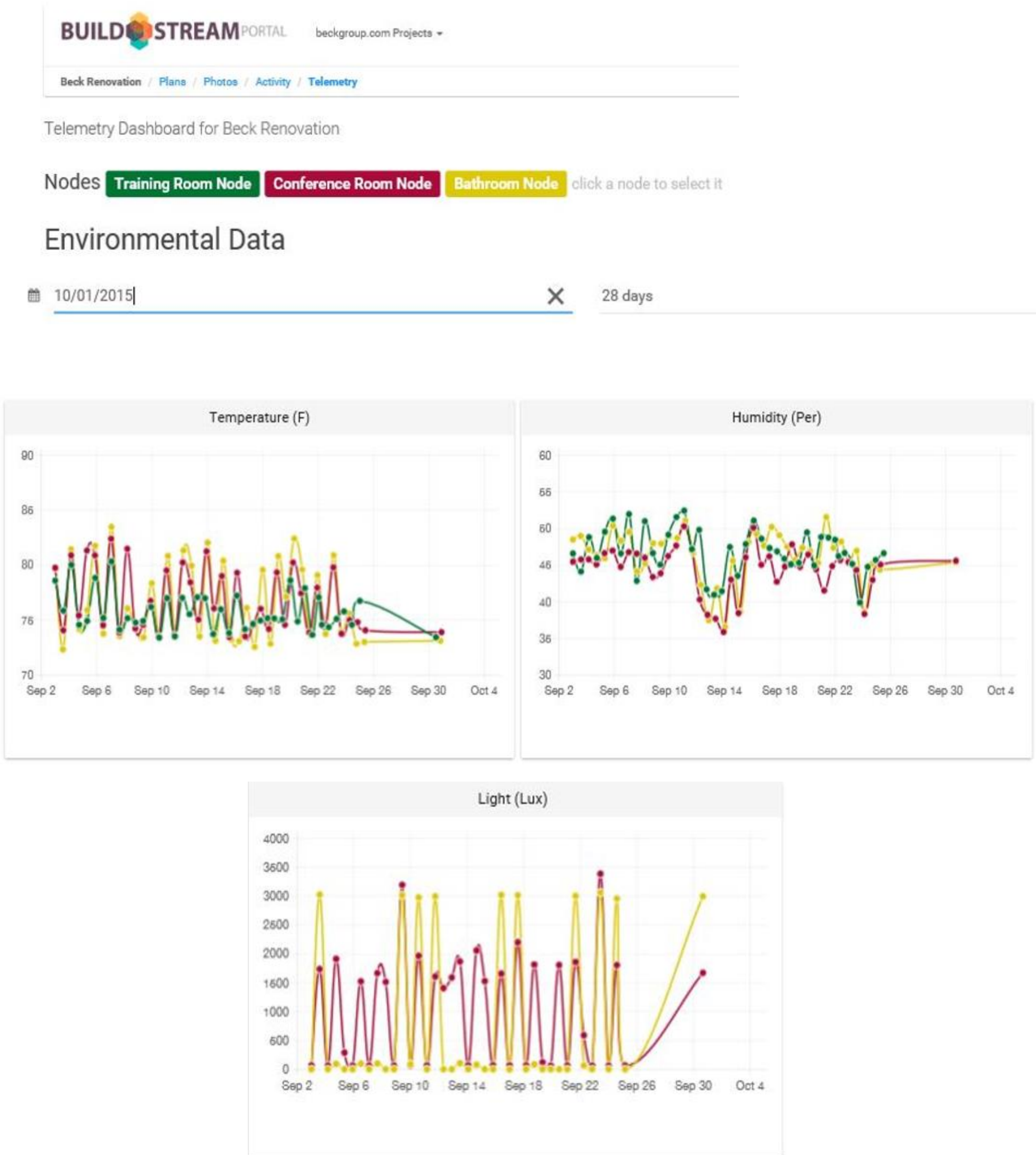


Figure 5.116 - data captured by the sensors installed at The Beck Group. Source: image courtesy The Beck Group

Regarding the light graphic, we assumed it was related to light emitted by electric fixtures since the training room data wasn't present in the graphics and it is the only room with openings. The bathrooms are the spaces that have more light during the days, consuming more energy.

Sensors can be installed in buildings during construction phase to check if the building is meeting the quality requirements. For example, noise sensors can check the maximum noise level allowed on a construction site; also, the temperature in which concrete is poured. Afterwards, construction sensors can be used for building comfort maintenance controlling the performance of materials and their usage.

Floor analysis (example in Figure 5.117) through TLS surveys can also provide data for monitoring the state of a building throughout its life and this information can be added to BIMs to understand the evolution of building elements and materials.

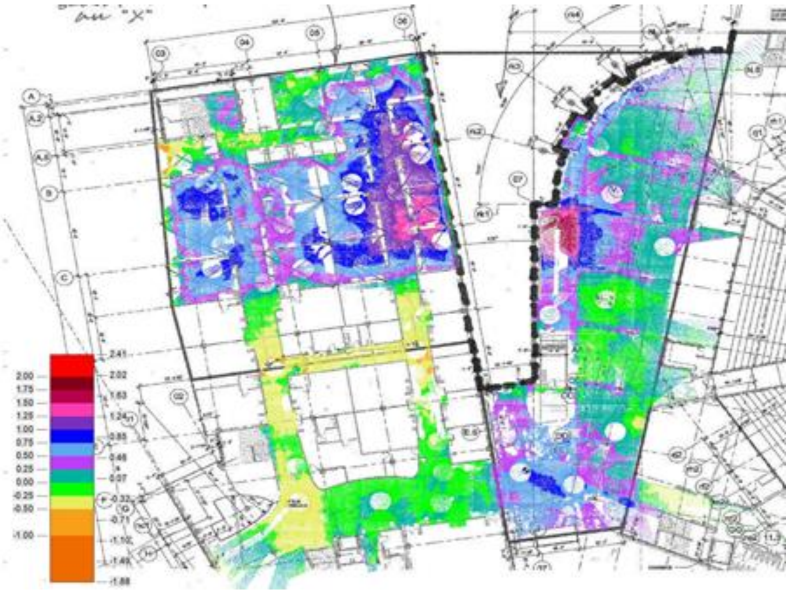


Figure 5.117- Analysis of the slab flatness. Source: image courtesy The Beck Group

To update the BIMs information and contribute for its maintenance, one can, for example, use *Verity* software from Clearedge[39] to compare the difference between what was modeled and what is actually built. Figure 5.118 shows on the left the difference between what was modeled (element with magenta color) and the element the software inferred from the point cloud (element with blue color). The difference between them is measured and a report is generated clearly clarifying whether measures are within the agreed tolerances or not. On the right side, we can visualize the modeled elements colored according to the tolerances values of their respective faces from the point cloud.

[39] http://www.clearedge3d.com/products/verity/

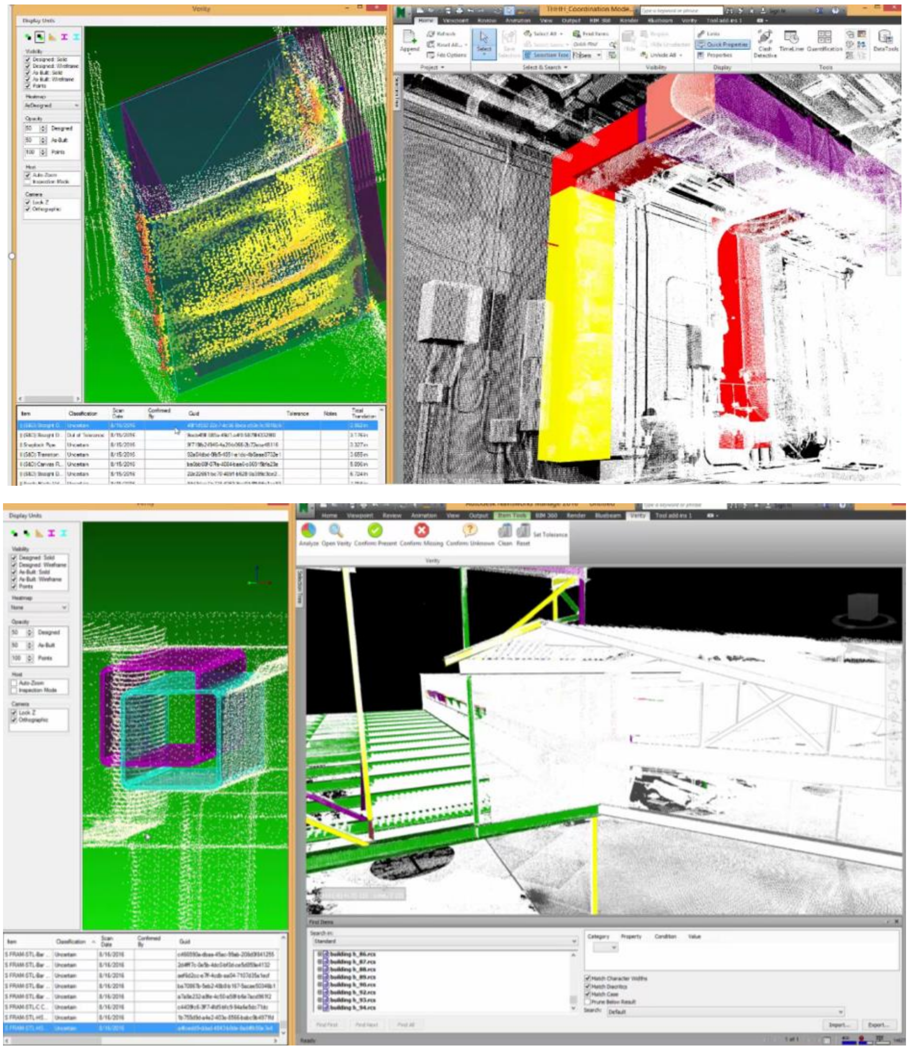


Figure 5.118 - Top image: Image of *Verity* elements comparison with PCM.

Bottom image: Elements not coincident.Source: image courtesy The Beck Group

The images in Figure 5.118 show elements that are out of tolerance not corresponding to the same position where they were built. Figure 5.119 shows elements within the tolerance, where we can see the blue and magenta elements are coincident.

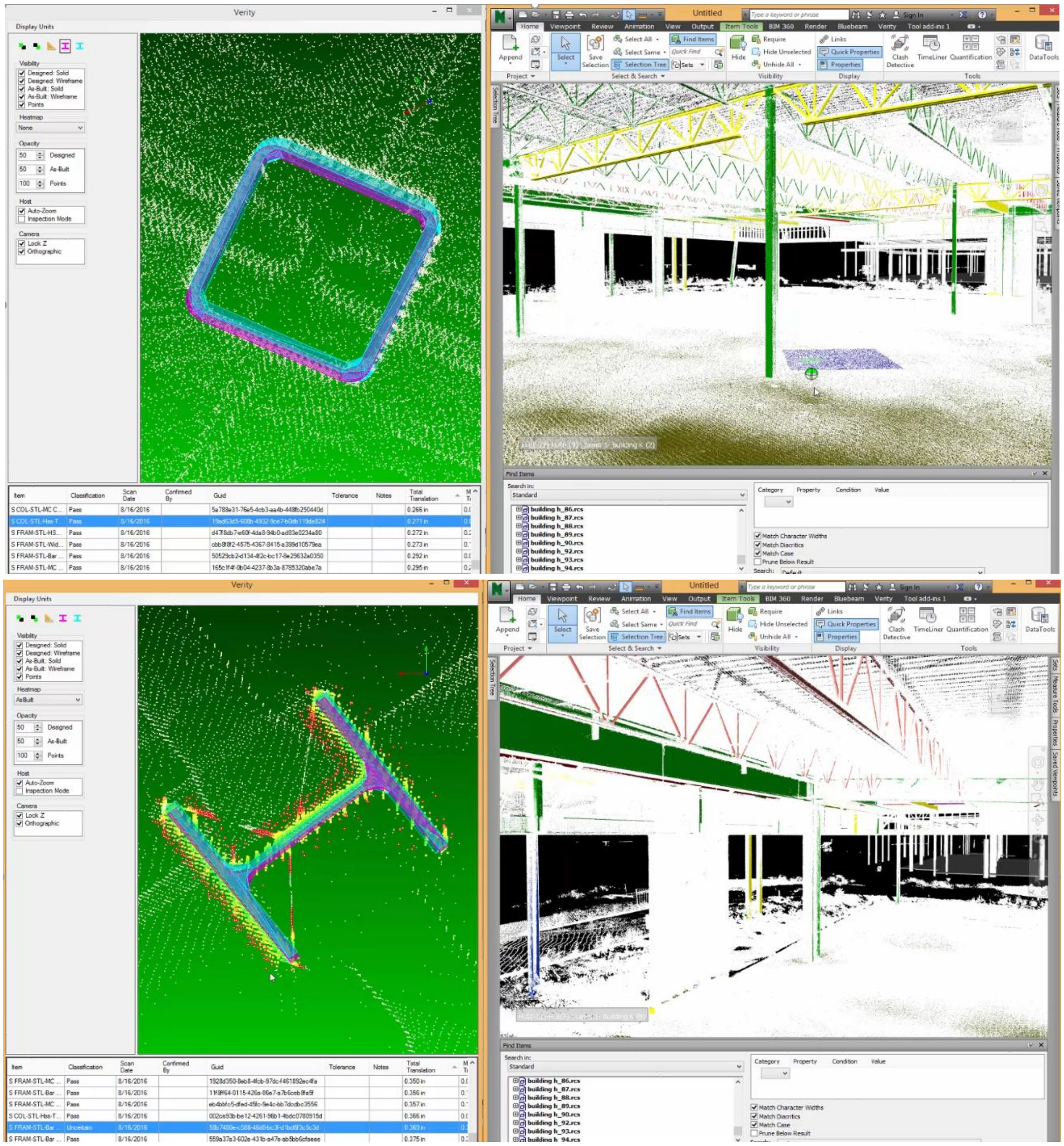


Figure 5.119 - Image of *Verity* elements comparison with PCM. Elements coincident. Source: image courtesy The Beck Group

Regarding the right side of Figure 5.118 and Figure 5.119 the software assumes the following colors and meanings:

- ❑ Green- element present
- ❑ Red- element missing
- ❑ Yellow – element out of tolerance
- ❑ Salmon – uncertain element
- ❑ Magenta – occluded element
- ❑ Cian – element with no data

This analysis of the as-is versus the as-designed situation is a valuable resource to update the building information in the BIMs. Usually, the construction of the buildings does not exactly correspond to the design drawings: this can be due to various reasons like miscommunications, adversity on site, change of intention not registered, among others. This process will allow to change what was thought to be on site and to provide a more accurate and up to date information for the next intervention.
The Verity variance data can be exported to *Autodesk® Navisworks®* to perform clash detection on the as-built position of any element, thereby reducing the likelihood of downstream rework and schedule delays from out-of-tolerance construction.

PCM also can be used in a coordination environment directly in *Autodesk® Navisworks®.* If point clouds are dense enough they can be used for clash detection. The clash detection tool relies on geometric intersections and finds geometry coinciding with a point. This does not work with sparse point cloud data. There are only two downsides to clashing a point cloud in *Autodesk® Navisworks®*. First, the point cloud is treated as one object per scan: the user can't pick individual points. Likewise, the clash detection has the same limitations. So, one can get a lot of clashes linked to a single scan and the whole scan turns red. The user needs to manage *Autodesk® Navisworks®'* clash visualization filters to make this information useful. The second limitation is that the scan data noise can introduce false positives into the clash detection process.

Besides clash detection, PCM in *Autodesk® Navisworks®* can be used as a verification tool. The user can walk through a model observing whether there be an object with no correlated scan data or if there is scan data with no correlated object. This can be automated through the use of the clash detection tool. Using the clash detection to do verification is like "inverted" coordination. Instead of looking for clashes, the user will be looking for no clashes: objects that don't have a clash, also don't have correlated points, or are so far from their correlated points that they do not register as a clash. So, anything in the model that does not clash with a point cloud is a potential problem. Again, noisy scan data can give false clashes, which in this case is a bigger problem since one is not looking at the clashes. This process should not be used with a PCM that is not cleaned.

5.4. Conclusions

The generation of as-built BIMs for existing building intervention planning is dependent on geometric and non-geometric information. The non-geometric information can consist in element materials, labels, fire rating information, manufacturer's information, non-visible interior material layers (materials inside walls, floors, roofs, etc), and construction systems information, among others. BIMs consist in 3D elements that work as containers for non-geometric information. For this reason, the first step in BIM is to set up and model the geometry referring to the building and after, or while generating it, link more information.

As-built BIM adoption problems, previously identified by Volk et al. (2014), refer to the analysis and generation of building geometry, that usually is a previous step to the link of non-geometric building information. The present thesis focuses mainly in finding guidelines to decrease the difficulty in generating the as-built BIMs elements (modeling geometry). Geometry and the 3D visualization are a small part of the as-built BIM potential; nevertheless, if it is one of the major issues for its adoption. For this reason, the case studies in Section 5.1 address the issue of handling uncertain data, objects and relations by focusing on how to use reality capture data and its outputs to provide missing data needed for project analysis. In Section 5.2., the case studies address the high modeling effort by focusing on critical analysis of BIMs, generated through PCM and CAD drawings, and on modeling (geometry analysis) workflows, followed by the possibilities of workflow efficiency improvement with automation. Section 5.3 describes several processes of monitoring buildings, specially during the construction phase, outlining processes of capturing building data that can contribute to updating the BIMs.

Prior to commencement of a survey, a clear understanding of accuracy requirements, modeling requirements (namely what information should the model contain), the level of interpretation and modelling tolerances required by the project, must be achieved by all parties (the survey, modeling and project teams). If this is agreed in the beginning, the probability of missing vital data for the project development will decrease. If communication is not clear among project stakeholders or if the requirements of the project change for some reason, the project team will need to acquire more data for the project analysis that is meant to inform the intervention decisions.

5.4.1. Missing and uncertain data

Section 5.1. describes case studies that handled the missing data issue through the acquisition of point cloud data and, additional imaginary integrated with 2D and 3D models. Relating to adding missing data through point cloud data generation, the study cases outlined the importance of planning the survey, with all parties understanding what the project needs are. Not all tools and methods are suitable for all buildings: the scale, materials and accessibility of a building play a major role in the survey planning. This is of course parallel to the time and money available. The “Ruseløkkveien” project demonstrated that ADP survey is a resourceful process if one has the knowledge and tools to do it. One can not simply pick up a camera and obtain useful data, it should be planned according to the building characteristics. The case study was included in the present thesis to demonstrate what can go wrong when this is not done.

Small building areas/details can be acquired by the architectural office to add missing data, through low cost handheld ADP surveys, as it was demonstrated in “Briskebyveien” project. This workflow could be used in a “daily basis” by architectural offices to acquire small amount of information in a fast and reliable way.

In bigger scales, the integration of ADP and TLS surveys in the planning of a building survey results in more completed data. The “Belém Palace” survey outlines the importance of integrating tools that complement each other, combining their strengths, and plan their use prior to the survey. The output of such survey will likely have a decrease in the missing information data.

Summarizing ADP point clouds can complement PCM data when the acquisition technique is structured and planned according to the object characteristics, providing usable data. One can use photogrammetric data to add missing building information. This process can be used for building details, small areas or big areas, where what will vary is the tool used (handheld camera, handheld with mast, drone, balloon with camera, among others).

During “Akersgata” project development, point cloud data was acquired after demolition of some elements and wall layers. This allowed a better understanding of what elements remained and what the invisible materials layers of the building were. It is an efficient process for verifying that a project is constructed as designed, and it contributes for the acquisition and understanding of parts of the hidden data. The point cloud data can be obtained through TLS survey (as described in the project) or through ADP survey.

ADP data can also be used as basis information for the projects, whenever this basis is missing. This can happen for example in the beginning of projects or competitions (projects that architectural offices try to “win”), when information about the site where the building is located is gathered by the team. There are cities where this information has to be legally provided by the municipality but there are other cities where the use of this kind of data is not controlled. The aerial ADP data can be very accurate for example through the integration of drones data with ground control points. The “Trinity Forest” project outlines the acquisition of aerial ADP data for developing design and construction phases.

ADP data with low accuracy can be used for volume studies in a very conceptual and draft phase, when the shape of the building is not yet defined but the team is interested in understanding the square footage and level of impact on the site and surrounding buildings. The “Vitusapotek Volvat” study describes how such volume studies are executed by Grape Architects to perform volume studies to assess impact in the surrounding urban environment.

The PCM can generate different outputs that serve as basis for modeling, like the contour line maps and ortho images. It is important when modeling to integrate different kinds of data from different kind of sources. Complementing data that visually supports the modeling (e.g. materials and special connections) can enhance the modeling workflow. The use of 360° photos associated with 2D drawings or 3D modeling web platforms is a resourceable workflow that one can use to confirm building data, while modeling it. Ideally, one would have the BIM tool in one screen and the web platform with the additional data on a second screen, that would be consulted while modeling.

The usage of additional data acquired during project development to complement missing information can be one option to handle the uncertain data, objects and relations.

5.4.2. High modeling/conversion effort

To handle the high modeling/conversion effort one has to understand the current workflows to analyse building geometry. One way of generating as-built BIMs that is often used is through CAD drawings (sections, plans, elevations). This information is usually outdated or reveals design intention, not what was constructed. It should be checked and if it no longer is a representation of the as-is state of the building, it should be used as a reference of the building development history, not as a base for intervention.

If CAD drawings are updated and are used as the basis information to model, the ‘manual measures input modeling method’ and not the ‘trace over modeling method’ should be implemented. Reference planes should be used to help creating tolerances and controlling element position and measurements. This omits dimensional inconsistencies that occur with the ‘snap modeling technique’ that occurs when one traces over information inside BIM software.

Comparing the modeling from CAD drawings with the modeling from PCM, it is easier to model from CAD drawings since they are usually very generic representations of the building, they don't vary vertically and horizontally within the same element (for example the vertical variation of an as-is wall). The dimensions tend to be even dimensions with clear rounded values and clean angles (instead of 45.876 degrees it will be 45 degrees, and the measure will be for example 1.5 meters instead of 1.4462 meters). The 3D elements will be modeled faster and the information is easier to visualize and interpret. However, this does not mean we will have a better or more correct BIMs. The information of how the building varies and all its imperfections, captured by point clouds, is in our opinion of great value and usually preferable to the interpretation of generic and simplified information. It also allows to annotate, for each element, information about the building element condition state, and the level of development of the BIMs element (or any relevant information).

Both “Ruseløkkveien” and “Sognsveien” projects started by generating a BIMs based on information from CAD drawings and ended up ordering a 3D TLS survey to have more updated and specific information. This was due to inconsistent and incorrect information detected throughout the project, resulting from a not updated basis. It is important to determine what kind of data is suitable to be used as a basis to generate the BIMs.

Adjusting BIMs elements is a time consuming, tedious and laborious task. It is very easy that the user forgets the bi-directional associativity of elements, which results in moving one element and pushing another element associated with the first one. It is not unusual that, if not fixed, one has to correct the element position several times. It is easy to pin each element, but when modeling the user has to be very methodic or this step will be forgotten.

Through the analysis of “Karl Johans Gate 8-10”, “Akersgata”Sur”, “Mosque El Jebel”, “Medica Sur” and “College Station Theater” projects, some as-built BIMs modeling conclusions were outlined. These case studies were developed in *Autodesk® Revit®* software, since it was the software in use by the companies. This said, the conclusions extracted from them intend to be guidelines transversal to other BIM platforms.

Modeling requirements should focus primarily on: what to model, how to develop the elements in the model, what information should the model contain, and how should information in the model be exchanged. The model should be coherent through all the elements development, a coherent model will be the result of a consistent process. “Karl Johans Gate 8-10”, “ Akersgata”Sur” BIMs are examples of how elements inconsistency can derive from the absence of modeling criteria, resulting in rework and more time spent in reusing elements for the project intervention design.

From our experience, the use of point clouds by architectural offices in the generation of as-built BIMs could improve. First, the whole PCM should be asked by the architectural office, additional to the segmented areas of the building and other data outputs. Communication between the office and the survey company about PCM specifications and future uses should be documented (for example in an IDM or a BIM Execution Plan). The architectural office should use point cloud editor software to manipulate point clouds during the project development and the delivery of segmented PCM. This allows architects to control and transform the data themselves. The architectural company should have technical skills to know what to ask for and how to use it appropriately. The team members who order and deal with point clouds should have training and guidelines to follow, which will decrease the discrepancy between the knowledge in the acquisition team and the team who used the collected data.

The point cloud data survey should be done after agreement of the project goal, standards, tolerances and modeling content. This will allow the survey team to focus on the most relevant information. For efficient use of the PCM, this should be segmented according to logical areas and decimated whenever possible according to the project goal. The use of point clouds can also be improved not only with more efficient workflows but also with inclusion of different kinds of survey information, like 2D reflectance images of point clouds and field annotations.

The BIMs generation though the PCM should be done with both files sharing the same coordinate system. The project coordinate system in the BIM tool should allow inserting point clouds without any manual translation or rotation from the user. Ideally, one uses the corner of a building or any element that is easy to identify in the scan and aligns it with the BIM tool's relative origin. The data can be segmented into several small files since it is registered on the same coordinate system (shared). The user can insert all the point clouds into the project without worrying about their position and orientation.

When modeling through PCM, the manual measures input modeling method and not the trace over modeling method should be implemented. The tolerances and even measurements are vital for BIM tools performance. Usually, BIM tools are more efficient with orthogonal and even measures and angles. When the measures and geometry are more “complex”, the software performance starts decreasing and error warnings start occurring or it is not possible to model.

In the modeling process, it is important to be aware of how much effort and time the team wants to spend with each element. Before modeling it is essential to analyse the different types of elements that are present in the building, understand which belong to the same family, how do they relate with each other, etc. This should be done in order to standardize and create one element that represents groups of elements with same characteristics and some instance variations that do not influence the type of element. To prevent a model to contain several element types with only slight dimensional differences, one should repeat elements, such as windows and doors, that are similar in size and design. It is assumed that most buildings are designed to have a set number of door and window types when constructed. When surveyed however, small differences can be identified in structural opening heights and widths. Rather than creating an element type for each small variation in size, an average measurement will be taken across all these similar elements. The modelling tolerance should be considered before creating a new element type. This will help understand the modeling approach and complexity. The more standardized a model is, within the defined tolerances, the better performance it will have.

Generic or non-parametric modeling should be avoided in elements that can be reused. The windows, doors and associated frames are within the elements that are usually reused. Cornices, statues, unique objects tend not to be reused for new elements and may be modeled with a fast non-parametric process. This is not considered the best workflow and when used should be agreed with the project team.

A parametric element has basic input parameters like height, width, position, etc., that can be edited and manipulated afterwards, resulting in a very flexible element. By providing appropriate parametric objects, it is not necessary anymore to edit the same type of element several times, namely, once for each occurrence of that element type. It would be a more efficient workflow if we change an element dimension and this change was applied to every element of the same type. In addition, the representation of specific elements, like windows, or of complex elements should be isolated from the point clouds with a high point density and modeled into software system elements. These system objects allow repeatability of the same element without a huge increase in the file size and the use of parameters for faster changes on element types.

Automated or semi-automated tools for elements shape extraction, elimination or reduction of repetitive tasks during the BIMs development, and analysis of environment or scenario conditions are a way of decreasing the modeling effort. The workflows with automated processes are more efficient since they can be adapted and repeated in the following projects, even if it takes some time developing.

5.4.3. Maintenance and updates in the BIMs

Appropriate usage of parametric objects is also useful for updating and maintaining the BIMs throughout the building lifecycle. Tolerances and standardization of elements and tasks should be implemented while modeling so it is a consistent method. When modeling, the highest hierarchy is the project goal and this will be reflected on the BIMs. Tolerances and standards are agreed according to that project goal.

The model elements should be developed with LOD 300 and, whenever this is not possible, comments should be made in direct connection to the relevant object. Repeating Section 4.4.2 definition, an element with LOD 300 is graphically represented as a specific object with specific size, quantity, shape, location, and orientation, which answers the needs of architectural projects. The LODs below 300 are too generic, and the ones over 300 have too much information for the architectural BIMs needs (at least in the project phases we studied).

Monitoring data, whether photos, PCM, sensor data, or data resulting from the comparison of PCM and BIMs can be a way of updating existing BIMs and having constant information added, documenting the building evolution and story, while evaluating possible prevention interventions for its enhancement.

6

Guidelines

This section outlines guidelines for as-built BIM workflows, based on Chapter 5. Following Chapter 4, we distinguish here between guidelines for as-built BIM data exchange requirements (Section 6.1.) and the guidelines for modeling as-built BIM (Section 6.2). Figure 6.1 illustrates a schematic diagram of the Chapter 6 subjects summary.

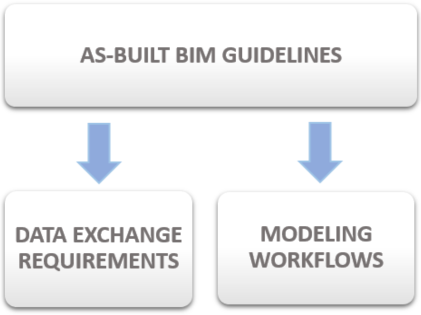


Figure 6.1- schematic diagram of the Chapter 6 subjects summary

These guidelines are built upon the project case studies of Chapter 5 and can contribute for better as-built BIM outputs. These guidelines are to be used as a basis and adapted for the different company and project needs and targets.

6.1. Guidelines for as-built BIM data exchange requirements

The aim of the BIM standards frames three key goals: formalizing the data sets by naming the elements, formalizing the exchange requirements by defining format exchanges, and formalizing the overall process model by producing documents containing the naming and formats exchange, including modeling processes and project team members.

Required data exchanges and interoperability between software used on the project, are essential and need to be agreed at the beginning of a project. Latest standards/specifications such as COBie or IFC and awareness of the different software used in a project will provide greater control of the data exchange and set rules to compensate interoperability issues. Specific software templates containing basic elements, views and naming conventions, should be defined in the beginning of the project. All stakeholders and contributors should work in that same software version.

Regarding scan data delivery, the raw scan data should be provided in different formats so that it can be used natively in different kinds of applications such as *Autodesk® Recap®, Autodesk® Revit® , Archicad, MicroStation, Autodesk® Navisworks®,* and so forth. These formats include RCS, PTS, PTX, PCG, E57, POD, IMP and many other formats.

Usually, file formats for point clouds are proprietary (property of commercial company and thus typically closed) and tightly linked to specific hardware. If such a file format is used, modelers are obliged to convert to a different file format whenever they are in need of inserting the point cloud into a software tool owned by a company other than the one owning the file format. When subsequently reconverting formats, there is usually loss of information or quality. Vendor-neutral formats like E57 should be added to the scan data delivery.

The level of decimation, file size and data transfer method should also be considered and agreed upon beforehand, and especially when requesting point cloud data.

6.2. Guidelines for the as-built BIMs modeling standardization

These guidelines are built upon the present thesis project case studies analysis. The information was collected from each case study and compared. The common workflows and the ones that were complementary were synthesized in the following guidelines for base information used in refurbishment projects.

6.2.1. Guidelines regarding data base for modeling

- ❑ Existing 2D CAD drawings can be used as a basis or support in the generation of the BIMs, under certain circumstances. Nevertheless, this data is usually more a record of how the building was intended to be, or how it was in a certain period of time and will most likely not correspond to the as-is state of the building. Using this data as a base to plan intervention without checking its accuracy can be an issue that will cost time and money to correct.

- ❑ An agreement about the project goals, standards and development should be prepared prior to the building survey. The survey team should be aware what is the survey being used for, what are the most important areas and what level of detail is needed.

- ❑ Areas of intervention should have a point density according to the purpose of its use.

- ❑ The PCM should be segmented into sensible project areas. This allows loading and unloading specific project areas along with their use in the project design. The PCM segmentation enhances BIM tools performance.

- ❑ Point clouds with a lot of noise should be cleaned. This means erasing unwanted points like reflection points from windows and mirrors, too distant data and sometimes cars, people, ongoing works, and furniture, among others. A cleaned point cloud allows higher output quality and a better visualization and interpretation of the data.

- ❑ Architectural offices should have the tools and skills to edit, analyze or transform point clouds. If these skills are not present, the understanding of the vocabulary that allows the architectural offices to order surveys, in an efficient way, should exist.

- ❑ The delivery method should include the entire point cloud model, segmented in different unified point clouds, in non-proprietary format, preferably;

- ❑ PCM on its own can be insufficient to supply a complete geometric framework for the building survey or to provide information required for the BIMs. The PCM should be connected to a survey control framework, and geolocated, for more accurate data.

- ❑ Additional point clouds can complement missing information in a PCM.

- ❑ Not all information can be obtained through the point clouds. For this reason, one should also acquire other kinds of information like field notes, photos, existing documents with the building evolution, construction reports, among others.

- ❑ It is important to choose the appropriate survey method for additional or new data. The tools used will vary according to project scale, material and complexity. It is vital to plan the data acquisition, from the tools and strategy point of view, in order to produce reliable data that is suitable for a certain purpose. The data added afterwards should rely on control data to be used properly, which can be survey control points, TLS PCM or in small size objects hand measurements.

- ❑ ADP data can be used to complement previous existing information or as the basis for the project site. This can be done in different phases of the project, with different levels of accuracy. The input used for photogrammetry can be as inaccurate as printscreens, or as accurate as the best quality photos associated with control survey. Low or high accuracy data should be chosen depending on the purpose and investment capabilities.

- ❑ Additional data, like 360° panoramic imagery associated with 3D models, or 2D data on web platforms or Trueviews, should be used to visually enhance the interpretation and generation of the BIMs. These web platforms can also be used as management tools for photos and metadata.

6.2.2. Guidelines regarding modeling process

The modeling workflows throughout three companies, described in chapter 5, and its comparison with guidelines from survey and modeling companies contributed heavily to the present guidelines development. The below tolerances and modeling guidelines are namely based on the three years experience and training inside the referred companies and also in their internal standard guidelines. They are to be interpreted as a guide and not as the correct and strict rule, as the tolerances and standards change across companies and countries and projects.

In the present guidelines, the level of interpretation and simplification of the point cloud data into BIMs elements, will be presented through example values, to explain a principle and not to be followed as the correct value.

The most effective method of dealing with deviations is to define the maximum tolerance by which the point cloud data will be allowed to deviate from the interpreted finish face. For example, in situations like deviation of walls from the horizontal or vertical plane, these guidelines will follow the round measurements to the nearest 5 millimeters. In the Solid Point Revit Survey Specification[40] used by Solid Point company, the modeling tolerance from the PCM is within 15 millimeters for walls, floors/slabs, columns, beams, grids, doors and windows. While the roof, ceilings, topography ,fixtures, furnishings and sanitary equipment are modeled with a tolerance within 30 millimeters. Plowman Craven company considers 3 levels for deviation tolerances present in Plowman Craven (2017): the low-level tolerance where elements are modeled to a tolerance of 60 millimeters from the PCM; the mid-level tolerance, with a 30 millimeters tolerance from the PCM; and the high-level tolerance, with 15 millimeters tolerance from the PCM.

Regarding the element modeling simplification, the present guidelines recommend the LOD 300 adopted from USA standards. Plowman and Craven (2017), from UK, defines that it has level of detail referring just to graphical information (LOD1, LOD2, LOD3), and adds level of information (LOI) and 'level of model definition'. There are several acronyms in use though the industry and although with the same purpose, they have some differences which cause confusion.

Regardless of these differences, the standard documents have the purpose of producing and receiving information in a consistent data format, in efficient exchange workflows between project stakeholders. The critical thinking of the modeling workflow and, the communication and agreement between all parts involved is the prime product of the thesis guidelines, not whether the tolerance is set to 5, 10 or 15 millimeters. It is in this set of mind one should interpret the following guidelines, where example values explain principles and should not to be taken as the correct values.

Starting Project File

The first step in a project is to set a starting project file with a coordinate system, this also applies to projects with point clouds. The project coordinate system in BIM tools should allow inserting point clouds without any manual translation or rotation from the user, regardless when the PCM is inserted. The BIMs file and PCM should always share the same coordinate system. Because the PCM is registered on the same coordinate system (shared), the user can insert all segmented PCM files into the project without worrying about their position and orientation. If one of the point clouds is removed from the project by accident, it can be inserted back and will be positioned into the same spot every time.

[40] http://www.solidpoint.co.uk/spec/

Set Coordinate System

Regardless of the coordinate system used to register the point cloud data, the workflow for setting up the coordinate system for a BIMs is identical.

❑ The project base point (local coordinate system) should be redefined to be a specific coordinate or describe a location of the building where the team would like the project base point to be located. This is done, because BIM software does not perform well with elements modeled far away from its local origin. The connection between the local coordinate system with the real world origin is kept. The coordinate values (X,Y) should not contain decimals since BIM software will not handle it correctly.

❑ Predetermined building corner axis or structural grid line intersection of existing building should align with the Y and X axis of the BIM software tools (Figure 6.1). The reason is also due to software performance. The true north should be exactly as it is in reality, and the project north should then be adapted so that the user is able to model orthogonally from the origin, the project base point (local origin). BIM tools allow to change between project north and true north, changing the visualization of the model orientation. Modeling with project north simplifies the modeling workflow for users and increases BIM tools performance.

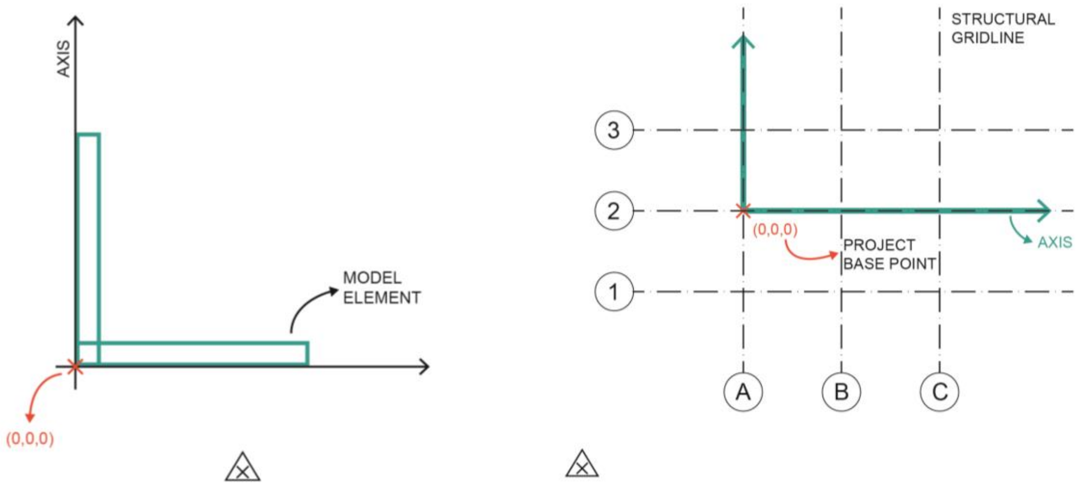


Figure 6.1- Predetermined building corner axis (image on left) or structural grid line intersection of existing building (image on right) should align with the Y and X axis

❑ The point cloud should be inserted based upon the shared coordinate system.

After the project base point (local origin and internal coordinate system) and the point cloud have been redefined and set, the project modeling can begin.

Project Modeling Standards

- ❏ Project Base Point shall not be rotated, moved, or altered. This would change the local coordinate system and differ from the shared coordinate system agreed between different stakeholders. The collaboration would be affected since the BIMs from different specialities would not match. Also the connection with PCM coordinate system would be lost.

- ❏ As-built model elements should be modeled in an existing phase group. Phase groups filter elements to the same “layer”. This should be followed so that when the design team starts modeling the new elements, they can be separated in a new phase group. One can control and differentiate what elements already exist, which parts of elements or whole elements are demolished, and where the new elements are. This is useful not only for visual analysis but also to extract quantity schedules.

- ❏ If only the existing documents are available, the as-built model elements should be generated by manual dimensions input instead of the tracing over method. Although existing documents can be imported into BIM tools, they should not since the accumulation of several drawings will decrease software tools performance. The model should, instead, be built to dimensions provided in documentation, with increment measures, like 0.1 millimeters, that follow the agreed tolerances. Where dimensional assumptions are made they should be annotated in the element or view.

- ❏ Before modeling, dimensions and tolerances should be defined. By setting tolerances one can decide which deviations will be documented in the BIMs. In reality, walls are not parallel to each other or walls are not exactly perpendicular to the floor/slab. Depending on the material type and lifetime of the building, these anomalies vary based on multiple conditions. For example thermal variations influence building element conditions, as they expand and contract with temperature. Using the snap dimension tool method will result in many dimensional differences depending on where the measurements are taken. All snapped dimensions are going to be slightly off from each other since reality is not as perfect, straight, parallel, or exact.

- ❑ If a PCM is available, the following guidelines should apply:

  - ❑ Element measures should be adjusted, for example, to the nearest 5 millimeters increments, with even measures. In reality, the thickness of built elements is not an exact dimension everywhere. It will be thicker in the joints, and in corners, and adding to this there is the measuring error. If the architect is to achieve required minimum dimensions then this needs to be taken into account. For this reason when using dimensions rounded to the nearest 5mm, one needs to assure minimum dimensions, so we need to round up. To ensure that minimum dimensions are on-site, the user needs to increase the width of the element. For example in the case of a 123 millimeters thick built wall, in the BIMs it becomes a 125 millimeters wall and not a 120 millimeters thick wall;

  - ❑ Elements should be modeled, for example, within 5 millimeters from the PCM, where possible and sufficient data is available. This guideline is represented in Figure 6.2, where a model element is positioned within the agreed tolerances. Elements with irregular surfaces (stone, brick, etc.) should be modeled, for example, within 10 millimeters from the PCM;

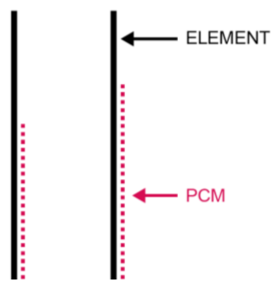


Figure 6.2- Model element within 5 millimeters from the PCM

  - ❑ Elements should be modeled parallel to the relative model origin axis and reference planes within the agreed tolerances. Polar angles (45 degrees, 90 degrees) within .02 degrees are to be reconciled to 45 or 90 degrees, as illustrated in Figure 6.3;

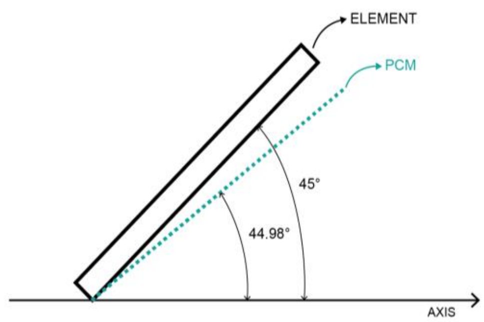


Figure 6.3- element within .02 degrees are to be reconciled to 45 degrees

- ❑ Elements that are intentionally built non-orthogonally should be adjusted, so that the tolerance from PCM does not exceed the agreed tolerance, and is within, for example, the maximum increments of 0.01 degree (decimal places beyond .xx are to be zeroed).

- ❑ Reference planes should be drawn parallel and, for example, within 5 millimeters tolerance from the origin axis, with even dimensions. Reference planes can be used to help creating tolerances and controlling element positions and measurements. This reduces dimensional inconsistencies that occur with the snap to point cloud modeling method.

- ❑ The as-built model should be generated through the PCM by manually placing the dimensions as they appear. This is defined as the manual measures input modeling method and should be used instead of the snap to point cloud method. Nominal, even, measures of standardized element dimensions should be analysed throughout the building and applied, whenever possible within the agreed tolerances.

- ❑ Where the tolerances are not possible or dimension assumptions are made, comments should be associated with the elements and views. One should create parameters connected to views and elements to annotate LOC, and deviation, this should be added to schedules, and to tags.

- ❑ The BIMs elements should be developed with LOD 300 and annotated with the element LOC if necessary. Whenever this is not possible, generic elements should be used and annotated. The definition of the minimum LOD that should be reached by all elements in the model will prevent the possibility of having a lot of detail, or very little information, in an object. Additionally, there can be objects of a small size represented on the project and similar objects with a bigger size not represented. An agreed minimum LOD for the same object type, will at least result in a coherent interpretation of reality. An element with LOD 300 is graphically represented as a specific object with specific size, quantity, shape, location, and orientation. This is the minimum LOD we recommend that answers the needs of architectural projects. The LODs below are too generic, and the ones above have too much information for the architectural BIMs needs. The minimum expected geometrical LOD of the BIM is to be driven by the level of design and/or construction at any phase, as well as the required BIM use for that stage of the project.

- ❑ The modeled elements should be parametric to be easily reusable and editable afterwards. These elements allow repeatability of the same element type without a huge increase in the file size and the use of parameters for faster changes on element types. The PCM representation of specific elements, like windows, should be isolated from the point clouds and modeled into BIM software tools into standard parametric elements.

- ❑ Implement standardized elements with nominal dimensions within the defined tolerances. It is assumed that most buildings are designed to have a set number of element types when constructed. When surveyed however, small dimensional differences can be identified. Rather than creating an element type for each small variation in size, average measurements within modeling tolerances should be adopted.

- ❑ Non-parametric elements should be avoided unless agreed with the team and annotated, in cases where it is a unique and complex element.

❑ If during the as-built modeling phase, assumptions were required to complete the project, these assumptions should be documented inside the BIMs.

❑ It is important that every modeler is actively doing their own quality assurance (QA) during modeling. One should always be double checking the model since it is very easy to forget BIM`s bi-directional element associativity. The final BIMs should be checked by another team member prior to handoff/delivery, which is considered the quality control (QC).

7

Final Conclusions and Future Work

This thesis intends to enhance processes of recording, document and manage information by establishing a set of workflow guidelines to efficiently model existing structures with BIM tools from point cloud data, complemented with any other appropriate methods. To this end, a set of research questions were formed and posed in Chapter 1, framing obstacles and directing the research focus in four parts contemplated in this chapter:

- ❏ 7.1. the different kinds of building data acquired;
- ❏ 7.2. the different kind of building data analysis processes;
- ❏ 7.3. the use of standards and as-built BIM and;
- ❏ 7.4 as-built BIM workflows and guidelines for architectural offices.

Sections 7.3 and 7.4 integrate and contribute to the solution of as-built BIM adoption problems identified by Volk et al. (2014):

- ❏ (1) the handling and modeling of uncertain data, objects and relations occurring in existing buildings in BIM;
- ❏ (2) the high modeling/conversion effort from captured building data into semantic BIM objects; and
- ❏ (3) the difficulty in maintaining BIM information.

The conclusion of the main question "*How to combine point cloud data with BIM processes in order to generate an efficient model for planning interventions in existing buildings?*" and its subsequent subdivision questions, are addressed in the following sections of this chapter.

Section 7.1. addresses the following questions:

1. What kind of data is needed to describe the current state of a building?
2. What kind of data can be extracted from 3D point clouds?
3. What are the limitations of point cloud data and how to overcome them?

Section 7.2. refers to the question:

1. How can data and its analysis, regarding existing buildings, be processed in BIM tools?

Section 7.3. refers to the question:

1. 5. How can standards contribute to as-built BIM workflows efficiency?

And finally, Section 7.4 refers to the questions:

1. How to handle and model uncertain data?
2. 7. What other techniques and methods can be used to gather more information?
3. 8. How to minimize the high modeling effort of existing buildings in BIM?
4. 9. How to maintain the BIMs?.

Afterwards, the overall contributions of the thesis are described, followed by the further work that is proposed to take this research forward.

7.1. The different kinds of building data acquired

There is a need for better use of documentation in which architectural intervention project decisions are made. **Different kinds of data, not just geometric, are needed** as base for the analysis of the current building state. Non-geometric information can refer to physical characteristics of the built fabric, such as materials, appearance and condition. Furthermore, environmental, structural and mechanical building performance, as well as cultural, historical and architectural values, style and age are vital to the understanding of the current state of the building. This information is necessary for further analysis allowing the understanding of the necessary actions to intervene.

It is important that one does not assume that existing documentation is a reliable depiction of the building as it is. The information should be **checked for accuracy**. If this is not the case, it should be used as historical document, to understand building evolution, but not as a base for intervention.

Accurate and up to date information can be generated through **ADP and TLS surveys**. The final product of ADP and TLS are the point clouds, which can be used together to **complement each other**. The combination of these techniques with traditional RTS survey provide an accurate and up to date base, that, along with other existing information, allow the planning of building interventions.

One can extract geometric information from point clouds directly through the PCM, or through PCM section images, ortho-images. Point clouds allow to perform **geometry analysis** connected with space usages and relations between elements by creating 3D models like surface models, parametric models and BIMs. Infrared thermal images can be integrated in the PCM to optimize the recognition of **thermal anomaly locations**. And reflectance images allow to understand the location of different materials in the building.

Point clouds are majorly used to extract building geometric information and perform **deviation analysis**. The limitations of point clouds are directly related with their use to extract geometry for virtual model generation.

One of the PCM limitations is that it can reach **large size files, containing unwanted data**. The solution can be the segmentation of the PCM into logical building areas and also its decimation, decreasing the point density and consequently the file size.

The workflow to extract information from the point cloud can be time-consuming, error-prone and can lead to a loss of vital information. This extraction process can potentially be eased through the **standardization of the modeling process** and use of **shape extraction automation tools**. The modeling process can be standardized in different levels: international, national, regional, company-wide. This introduces a balance between fairly generic and abstract levels of standardisation and highly specific modeling agreements within a company.

Another limitation of point clouds is that points are still just geometric points with no intelligence associated. One should be able to **attach metadata to a set of points**, assigning them with the building element information. Thus, attribute characteristics to a set of points would function as walls, doors, windows, etc. If each point cloud could have this sort of information, the “dumb” point cloud would be replaced by a “smart” one. This would mean that the current workflows to generate models from point clouds would be no longer relevant. Point clouds would be segmented and classified by unique identifiers and integrated in the BIMs as distinct objects. The biggest challenge is to figure out how to assign the metadata to millions of points simultaneously and integrate them in BIM tools. This can be seen as future work.

7.2. The different kinds of building data analysis processes

BIM as a process of structuring and analysing information, allows to understand geometry and how spaces and elements relate. One virtually generates the object in study, which requires profound knowledge of the building or object. Following the 3D model generation, multiple analyses can be made. These include quantities and cost estimation analysis from selected elements, clash detections and coordination between several models with different data (for example checking the architectural model with the structural model from engineers); energy analysis, wind and solar studies, life-cycle analysis (LCA), deformation analysis, and so forth.

When studying a building, the next step after acquiring and processing data is to analyse the information. There are different types of analysis like **geometry analysis** and **current state of building analysis**. The analysis of the current state of the building **through point cloud data** can be: material analysis through radiometric studies; material temperature visual analysis, through the projection of infrared thermography in PCM; and, building deformation analysis.

In addition or besides the point cloud data analysis, one can perform **BIM analysis** to study how to enhance the **project performance**. BIM processes use different kinds of software tools to interpret and digitally record physical and functional characteristics of the as-built environment. Following the 3D model generation, there are multiple analyses one can do. These include massing and area studies, 3D design coordination analysis, 4D scheduling analysis, 5D quantities and cost estimation analysis, energy analysis, wind and deformation analysis, among others.

BIM benefits resulting from these analysis processes are: the improved information exchange and interoperability; the elimination or reduction of unbudgeted changes on projects; the increase of quantities and cost estimation accuracy; the clash detections which provide time and cost savings; the reduction in re-works due to enhanced quality control and design coordination; the enhanced data management, quality assessment and reporting tools. These valuable outcomes are equally present in BIM for new buildings and BIM for existing buildings.

7.3. The use of standards and as-built BIM

One of the reasons why standards are needed is the structure and improvement of the collaboration not only with outside parties but also inside architectural offices. Data and workflow standards are very hard to implement daily, in a practical way, resulting in **confusing data and workflows**. Such confusing data and workflows reduce the quality of communication and project outputs.

As-built BIM standards, exactly like BIM standards, contribute to the creation of reliable and useful information. These standards maximize the project production through **a coordinated and consistent approach**, ensuring high-quality deliveries and, efficient data sharing and communication in multidisciplinary projects. In general, BIM standards contain data structure and identifier standards, exchange requirement standards, and process model standards. These elements allow to create a standardized understanding of what the information exchange really is, to specify which information to exchange and when to exchange the information, and to standardize formats for information exchange. These standards are typically defined and described for new building projects, but should also be there for working with and intervening in existing buildings.

Several challenges are hampering BIM software adoption for planning interventions in existing buildings. Namely, the required modeling/conversion effort from captured building data into semantic BIM objects; the difficulty in maintaining information in a BIM; and the difficulties in handling uncertain data, objects, and relations occurring in existing buildings. These are the three key challenges that have also been put up by Volk et al. (2014), and which are strongly recognised in practice (Chapter 5).

In Chapter 5 and 6, we therefore developed a case for devising BIM **workflow guidelines for modelling existing buildings**, aiming to decrease the effects of those challenges as much as possible. The proposed content for BIM guidelines includes tolerances and standards for modelling existing building elements. This allows stakeholders to have a common understanding and agreement of what is supposed to be modelled and exchanged. It also allows the production of modelling outputs that are of later use to other people, and it allows planning the usage of (semi-)automatic tools in combination with the results of these outputs.

7.4. As-built BIM workflows and guidelines for architectural offices

As-built BIM adoption problems refer mainly to the analysis and generation of building geometry, which usually is a previous step to the link of non-geometric building information. For this reason the present thesis focuses mainly in finding guidelines to decrease the difficulty in generating the as-built-BIMs elements.

To **handle uncertain data and unclear or hidden semantic information**, one can complement the original data with additional missing information. The workflows in the present thesis address mainly the missing visible information. In the case of refurbishment projects, the **hidden information can be acquired to some extent with ADP or TLS surveys after demolition** of some elements and wall layers. This allows a better understanding of the non visible materials layers of a building element whenever it is a partial demolition. This process is only useful if a part of the element material is removed, it can not be applied to the non-intervened elements. Acquiring structural, concealed or semantic building information is challenging. Future research could focus on non-destructive techniques such as ground penetrating radars, radiography, sonars or electromagnetic waves for the acquisition of non visible data.

The handling of uncertain data, objects and relations can be done by **integrating different kinds of data from different kinds of sources**. Workflows to connect them in a more integrated way should be implemented. Different workflows can create additional missing information, used to complement or as a base for decision making when no data is available. Different kinds of information can be used like photos, additional point cloud data and, CAD and/or hand drawing, survey notes and 360 imaginary associated with 2D plan or 3D models web platforms.

Relating to adding missing data through point cloud data generation, the study cases outlined the importance of **planning the survey**, with all parties understanding what the project needs are. In addition to accuracy, the level of interpretation and modeling tolerances, required by the project, must also be **agreed and understood**. Not all tools and methods are suitable for all buildings: the scale, materials and accessibility of building play a major role in the survey planning.

To handle the **high modeling/conversion effort,** one has to understand the current workflows to analyse building geometry. As-built BIMs are majorly **manually generated through CAD drawings and/or PCM data**. These are used as a geometric basis from where information is extracted. The information used to plan the building intervention should be checked, **confirming it is a representation of the as-is state of the building**.

The **3D survey techniques** to capture the as-is state of the building **should be integrated** in the as-built BIM workflow to capture the building data in which intervention decisions are made. The output of these techniques should be integrated with different kinds of data to provide the most accurate and complete basis. The architectural company should have **technical skills** to know what to ask for and how to use it appropriately. The team members who order and deal with point clouds should have training and guidelines to follow, which will decrease the discrepancy between the knowledge in the acquisition team and the team who will use the collected data. This can lead to a **need of new groups inside companies, the technological groups, whose job is to support and improve the usage of new technology**. Laser scanning and photogrammetric surveys are part of the new technologies that are essential for the future of every company. Not only is accurate information needed in the beginning of existing building intervention projects, it is also highly important to control the quality of construction, comparing the as-planned with the as-is. Surveying and modeling a building is the best way to know the building, to understand how it works, how it was constructed, what is its history. The merge of this information with the intervention design team will create more efficient workflows and better outputs. When the company does not have the means to hire people with these skills, it is important that someone in the team still follows the surveys and is in charge of the communication of project intentions.

Modeling requirements should focus primarily on the content of this process: what to model, how to develop the elements in the model, what information should the model contain, and how should information in the model be exchanged. The model, independent of how high the level of detail and level of development are, is a simplification of reality. In fact, **there is actually no need to represent the building complexity in a BIMs if it is just used for visualization**. For this purpose one can consult the PCM. Most architects prefer to have surfaces than points but in reality you can read and understand the points and, when the user gets familiar with this different way of working, it is faster, more accurate (less interpretation) and there is no simplification of the building, as is the case in BIM. When modeling, it is important to **be aware of how much effort and time the team wants to spend with each element**. What needs to be in the models (this means any potential reduction in LOD, Accuracy, Scope of work, etc) should be discussed prior to the scanning and modeling.

The point clouds survey should be done after stipulating the project goal, standards, tolerances and modeling content. This will allow the survey team to focus on the most relevant information and **follow a specific survey strategy**. For efficient use of the PCM, this should be segmented according to logical areas and whenever possible and according to the project goal decimated. The PCM and BIMs should share the same coordinate system. The project should be setup accordingly. When modeling through PCM, and CAD drawings, the manual dimension input modeling method and not the trace over modeling method should be implemented. In a refurbishment project, the model elements should be developed with LOD 300 and whenever this is not possible, comments to the element should be made. Generic or non-parametric modeling should be avoided, and parametric modeling criteria should be established. This will be also useful for updating and maintaining the BIMs throughout the building lifecycle. Tolerances and standardization of elements and tasks should be implemented while modeling, so that it is a consistent method.

Tolerances and modeling guidelines differ across companies and countries. This is not necessarily bad, on the contrary. Regardless of these differences, the standards documents have the purpose of producing and receiving information in a consistent data format, in efficient exchange workflows between project stakeholders. The **critical thinking of the modeling workflow**, and the **communication and agreement between all parties involved in the project** are the prime effects aimed at in listing the guidelines in this thesis (Chapter 6), in direct connection with guidelines and working methods in the practice (Chapter 5). products of these thesis guidelines.

The establishment and agreement of modeling tolerances and the level of development and detail present in the BIMs, between the different parties involved on the project, is more important than which of the **existing definitions of LOD** is currently in use in the AEC industry. There will always be issues with the adoption of standards in (architectural) companies. For example, the use of LOD is not yet implemented in most architectural offices. One can see the benefits of using it, but there are some obstacles. LOD should not be a comment in a BIMs element, it should be a parameter that controls visibility settings and information filters. To develop these parameters to each element, one needs to invest time and develop software tool skills. This leads to the question who is going to pay for it. If it is not a client requirement, then it is unlikely it will be done. The research on how to simplify standards, applying them in a practical workflow can be a future work.

Modeling the information of the existing building is an analysis of the geometry and spatial element connection. When one wants to study an object, it does not make sense that someone else is hired to study the raw data and just give the resume of what is his/her interpretation. The same applies to Building Information Modeling. If one wants to know the building that is going to be intervened, it is crucial that the modeling is done in-house. One should have a deep knowledge of the object and make their own interpretation that will influence the intervention. If the model is done externally, it will be double work because hours will be lost to understanding and probably adjust it. For this reason, **it is recommended that the BIMs are not outsourced**. If the model is outsourced, external parties should be aware of what will be important for the intervention and needs to be modelled, what elements can just be visualized in the point cloud, what level of development and detail the elements should have, and they should understand the importance of all elements being standardized and parametric. Automated or semi-automated tools for element shape extraction, elimination or reduction of repetitive tasks during the BIMs development and, analysis of environment or scenario conditions are a way of decreasing the modeling effort. The **workflows with automated processes** are more efficient, because the scripts can be adapted and repeated in several projects. The automation of shape recognition, similarly to outsourcing a BIMs, gives rise to the issue of the geometry analysis not being done by the parties that study and plan the intervention. If in one side, the effort of generating the geometry is reduced, in the other, **the user has to verify it and has to understand** its dimensions and relations with other elements. Possibly, the intervention is in a specific building area and the study of the entire building is not needed, but if the intervention is in the whole building, a deep study of the geometry and building elements relations and values should be done. The automation of element shape recognition difficult the study of geometry through modeling.

This also gives rise to questions about the **parametric features and how to add semantic information**. Maybe not all elements should be automatically generated but just some specific ones. This can be seen as a future work, how to automate shape recognition into parametric elements, where the user has control on the level of development and information detail of each element.

To update a BIMs during the building life-cycle, one needs to acquire the as-is building state information. Monitoring data, whether constituted by photos, PCM, sensor data, or data resulting from the comparison of PCM and BIMs can be a way of updating existing BIMs. It allows continuously adding information, documenting the building evolution and story, and evaluating possible prevention interventions for its enhancement.

8
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